CHAPTER IV
RESULTS AND DISCUSSION

4.1 Model Validation

There are two cases for testing the control in this thesis. The first case is gravitational flow tank and the second case is the plug-flow reactor and CSTR.

4.1.1 Gravitational Flow Tank with Control System

The gravitational flow tank model is used for testing the control system. The controllers are feedback, feedforward, cascade, and dynamic matrix control. The feedback controller is the proportional-integral-derivative (PID) controller. The feedforward controller is a proportional controller. The response curve of the gravitational flow tank without controller is shown in Figure 4.1. The gravitational flow tank was started at the conditions of height = 2.05 ft, velocity of outlet line = 3.4 ft/s, and flowrate of input line per tank area = 0.311 ft/s. At steady state, the height of the water in the tank will reach 4.6546 ft.

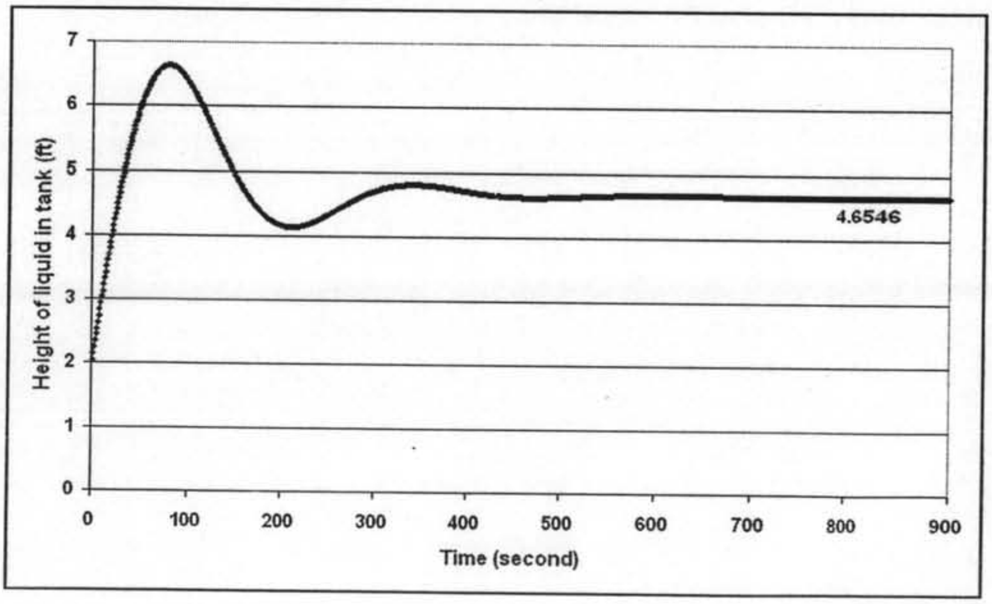

Figure 4.1 Response curve of the controlled variable, height, at steady-state of gravitational flow tank.

4.1.1.1 Feedback Control

The control system illustrated in Figure 4.2 is operated by sending the process output signal back to the controller. Decisions are based on such "fed back" information, which is then implemented in the process. This is known as a feedback control structure, and it is one of the simplest, and by far the most common, control structures employed in chemical process control. As shown in Figure 4.2, the level of liquid in the tank was controlled by the PID controller. The initial conditions are: flowrate of input line per tank area = 0.311 ft/s and height of water in the tank = 4.6546 ft.

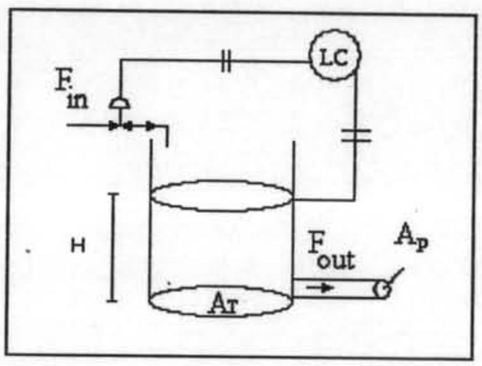

Figure 4.2 Gravitational flow tank with feedback control.

Results of the response curves of the manipulated variable and the height of liquid level in the gravitational flow tank by using feedback controller by Fortran program are shown in Figures 4.3 to 4.6. Figures 4.3 and 4.4 show the disturbance of input volumetric flowrate per tank area changing from 0.311 to 0.35 ft/s and Figures 4.5 and 4.6 show the setpoint of liquid height changing from 4.6546 to 4.7 ft. The controller is adjusted every second. Parameters used for adjusting the controller are K_C, τ_I, τ_D. The tuning parameters by Ziegler-Nichols's method are K_u = 0.0193 1/s^2 and P_U = 44 s. The result of tuning is shown in Appendix C. The value of parameters by using Ziegler-Nichols's method are K_C = 0.01158 1/s^2, τ_I = 22 s, and τ_D = 5.5 s. The Integral Absolute Error (IAE) of the height of liquid level in the tank is 0.74885 ft*s when disturbance occurs and the IAE is 1.07093 ft*s when the setpoint changes.

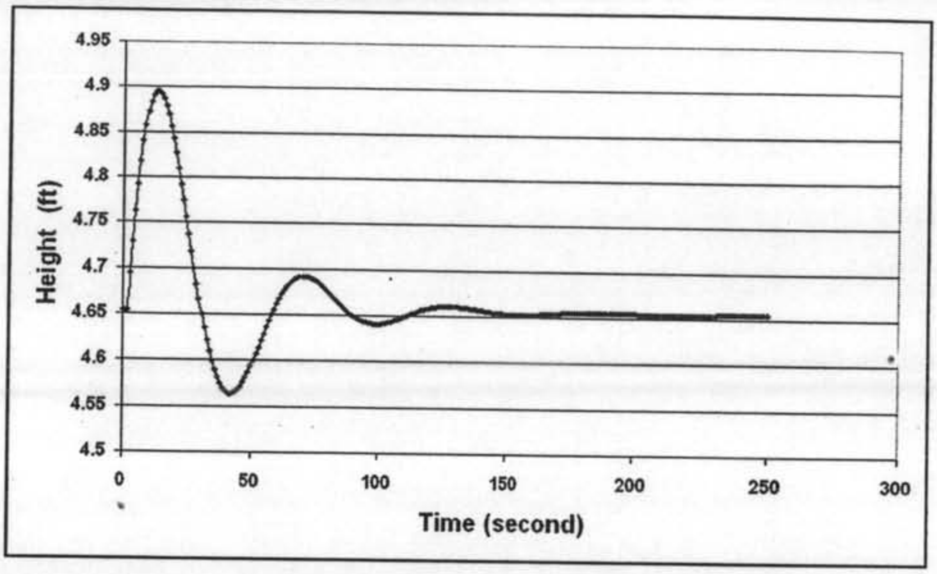

Figure 4.3 Response curve of controlled variable, height, of feedback control of gravitational flow tank with the disturbance of input volumetric flowrate per tank area changing from 0.311 to 0.35 m/s. (Tuning parameters: $K_C = 0.01158\ 1/s^2$, $\tau_I = 22$ s, and $\tau_D = 5.5$ s)

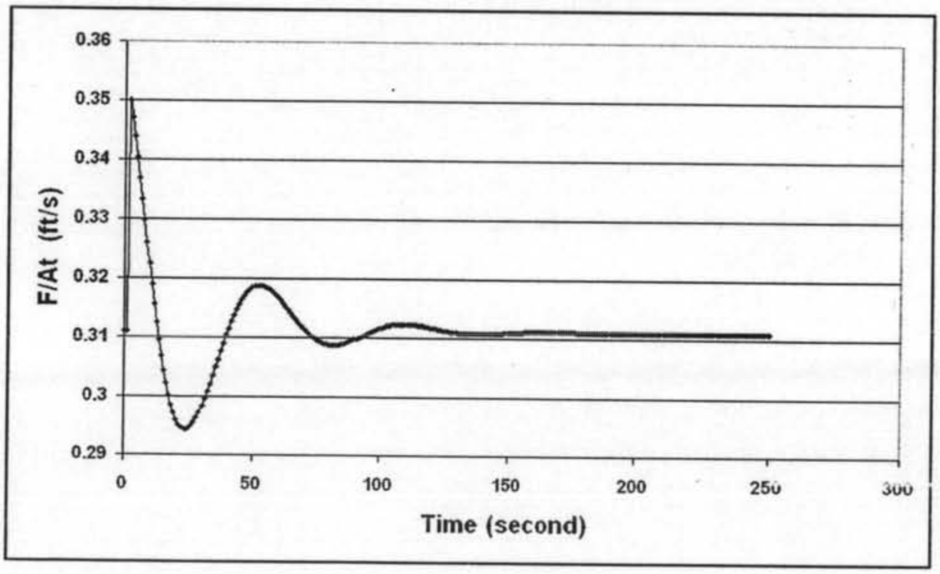

Figure 4.4 Response curve of manipulated variable, input volumetric flowrate per tank area (F/At), of feedback control of gravitational flow tank with the disturbance of input volumetric flowrate per tank area changing from 0.311 to 0.35 m/s. (Tuning parameters: $K_C = 0.01158\ 1/s^2$, $\tau_I = 22$ s, and $\tau_D = 5.5$ s)

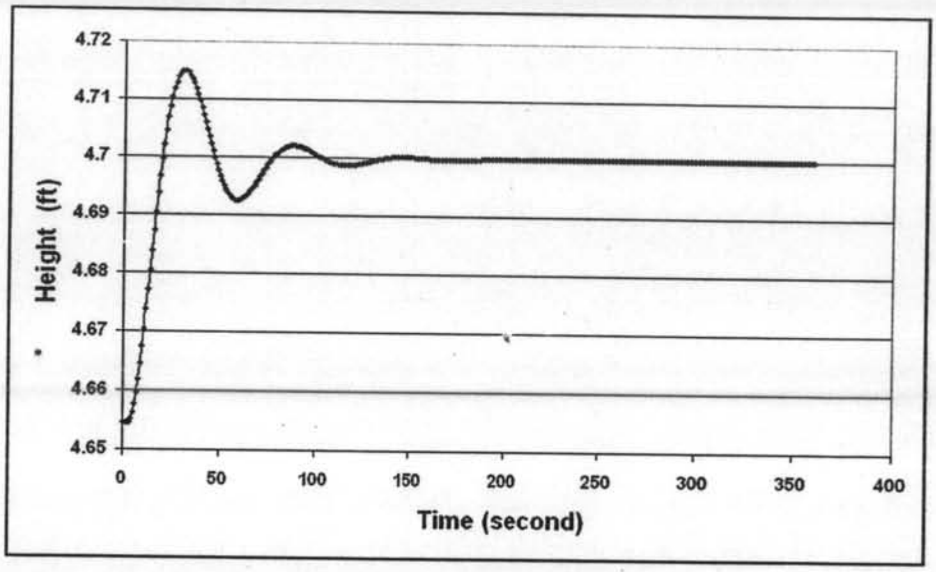

Figure 4.5 Response curve of controlled variable, height, of feedback control on gravitational flow tank after setpoint of height changing from 4.6546 to 4.7 ft. (Tuning parameters: $K_C = 0.01158\ 1/s^2$, $\tau_I = 22$ s, and $\tau_D = 5.5$ s)

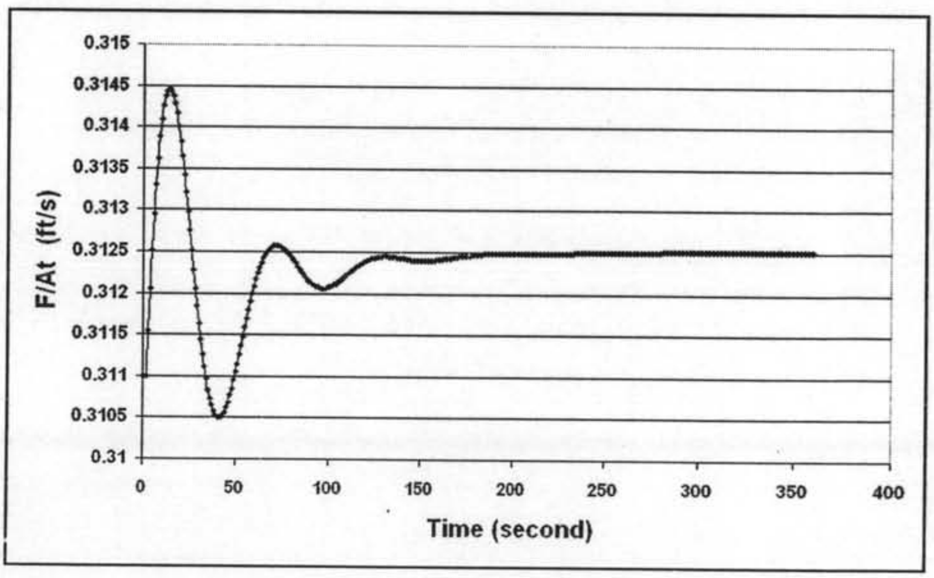

Figure 4.6 Response curve of manipulated variable, input volumetric flowrate per tank area (F/At), of feedback control on gravitational flow tank after setpoint of height changing from 4.6546 to 4.7 ft. (Tuning parameters: $K_C = 0.01158\ 1/s^2$, $\tau_I = 22$ s, and $\tau_D = 5.5$ s)

4.1.1.2 Feedforward Control

In Figure 4.7 the model has a situation in which an incoming disturbance gets directly communicated to the controller and the decision is made before the process is affected by the incoming disturbance. This is the feedforward control structure since the controller decision is based on information that is being "fed forward". The initial conditions are: flowrate of input line per tank area = 0.311 ft/s and height of water in the tank = 4.6546 ft.

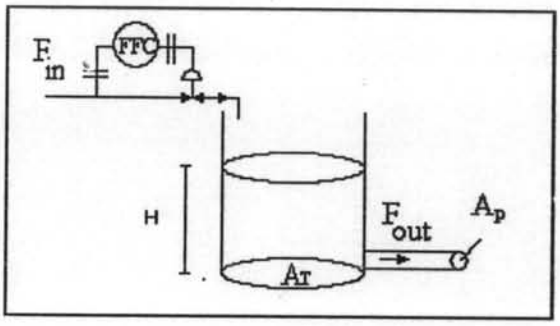

Figure 4.7 Gravitational flow tank with feedforwardcontrol.

The results of the response curve of the manipulated variable and the height of gravitational flow tank by feedforward control using a Fortran program are shown in Figures 4.8 to 4.11. Figures 4.8 and 4.9 show the disturbance of input volumetric flowrate per tank area changing from 0.311 to 0.35 ft/s and Figures 4.10 and 4.11 show the setpoint of input volumetric flowrate per tank area changing from 0.311 to 0.35 ft/s. The controller operation is like the feedback system. It is adjusted every second. Tuning by Ziegler-Nichols's method gives K_u = 2 $1/s^2$ and P_U = 2 s. The result of tuning is shown in Appendix C. The parameters by using Ziegler-Nichols's method are K_C = 1.2 $1/s^2$, τ_I = 1 s, and τ_D = 0.25 s. The IAE of input flowrate per tank area is 0.03509 ft when disturbance occurs and the IAE is 0.35 ft when the setpoint changes.

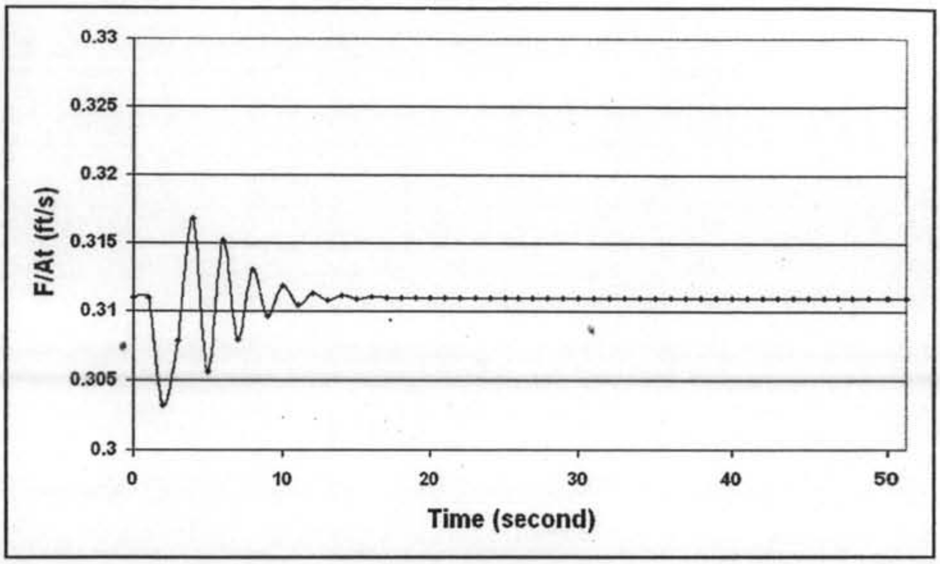

Figure 4.8 Response curve of manipulated variable, input volumetric flowrate per tank area (F/At), of feedforward control on gravitational flow tank after flowrate in per tank area changing from 0.311 to 0.35 ft/s. (Tuning parameters: $K_C = 1.2\ 1/s^2$, $\tau_I = 1$ s, and $\tau_D = 0.25$ s)

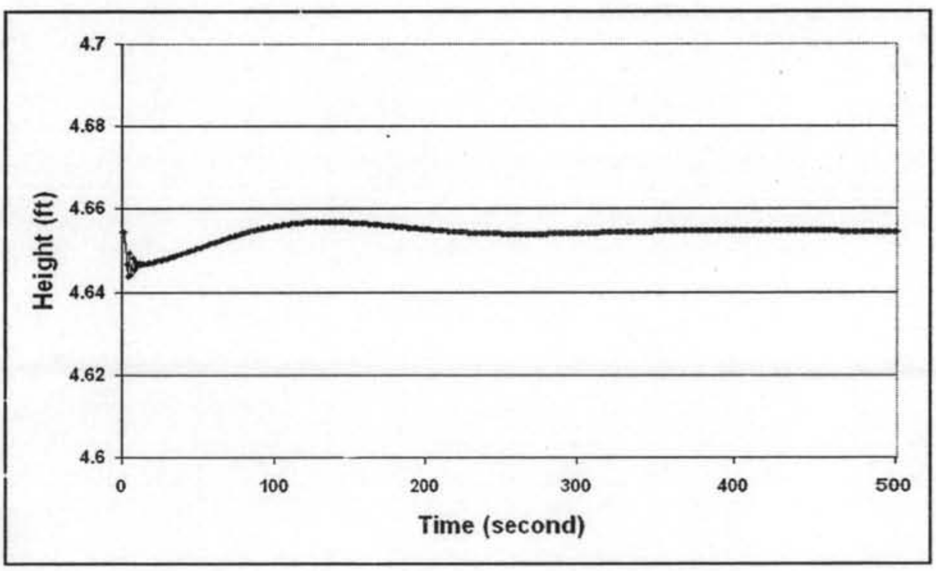

Figure 4.9 Response curve of height of liquid level in tank of feedforwardcontrol on gravitational flow tank after the disturbance of input volumetric flowrate per tank area changing from 0.311 to 0.35 ft/s. (Tuning parameters: $K_C = 1.2\ 1/s^2$, $\tau_I = 1$ s, and $\tau_D = 0.25$ s)

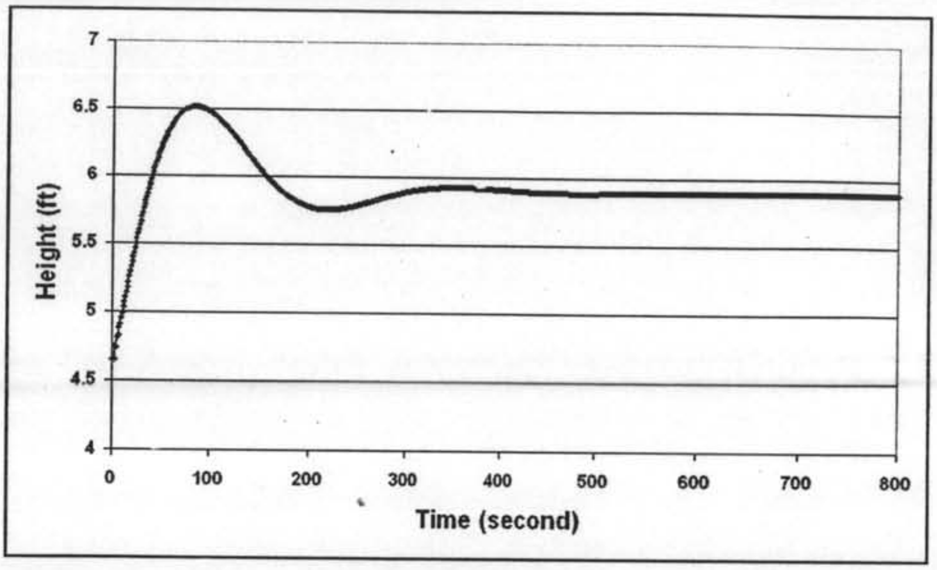

Figure 4.10 Response curve of height of liquid level in tank of feedforward control on gravitational flow tank after setpoint of input volumetric flowrate per tank area changing from 0.311 to 0.35 ft/s. (Tuning parameters: $K_C = 1.2\ 1/s^2$, $\tau_I = 1$ s, and $\tau_D = 0.25$ s)

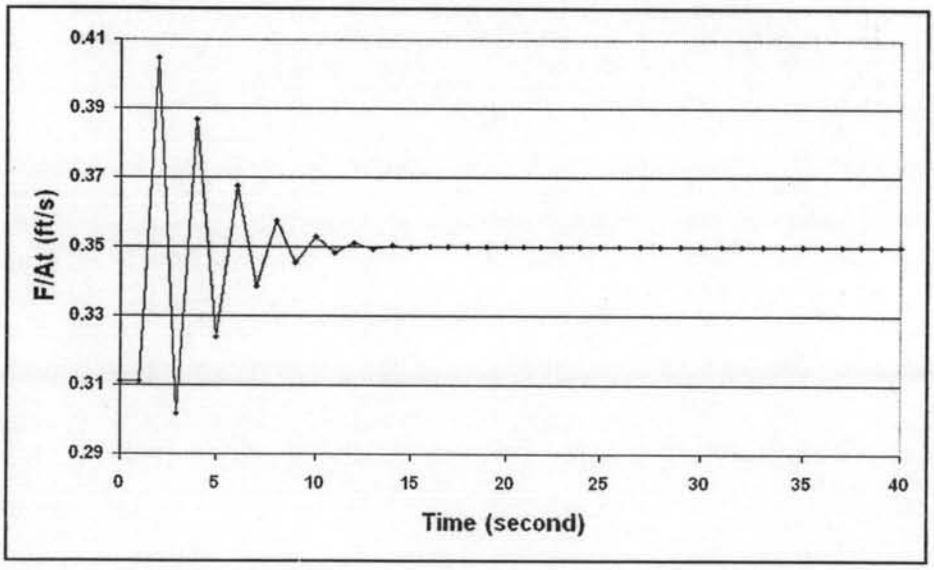

Figure 4.11 Response curve of manipulated variable, input volumetric flowrate per tank area (F/At),of feedforward control on gravitational flow tank after setpoint of input volumetric flowrate per tank area changing from 0.311 to 0.35 ft/s. (Tuning parameters: $K_C = 1.2\ 1/s^2$, $\tau_I = 1$ s, and $\tau_D = 0.25$ s)

4.1.1.3 Cascade Control

The cascade control is composed of two controllers tested with the gravitational flow tank model. The primary (master) controller is the level control and the secondary (slave) is the flow control, as shown in Figure 3.6. The response curves of the cascade controller are shown in Figures 4.12 to 4.15. The initial conditions are: input flowrate per tank area = 0.311 ft/s and height of water in the tank = 4.6546 ft. Figures 4.12 and 4.13 show the disturbance of input volumetric flowrate per tank area changing from 0.311 to 0.35 ft/s and Figures 4.14 and 4.15 show the setpoint of liquid height changing from 4.6546 to 4.7 ft. Tuning by Ziegler-Nichols's method gives K_{u1} = 0.33339 1/s^2 and P_{U1} = 2 s for the primary controller and K_{u2} = 2 1/s^2 and P_{U2} = 2 s for the secondary controller. The result of the tuning is shown in Appendix C. The parameters of the primary controller are K_{C1} = 0.200034 1/s^2, τ_{I1} =1 s, and τ_{D1} =0.25 s. The parameters of the secondary controller are at K_{C2} =1.2 1/s^2, τ_{I2} = 1 s, and τ_{D2} = 0.25 s by using Ziegler-Nichols's method. The IAE of height of the cascade controller with the disturbance is 0.11467 ft*s and the IAE of the controller with the setpoint change is 0.44013 ft*s when the setpoint changes.

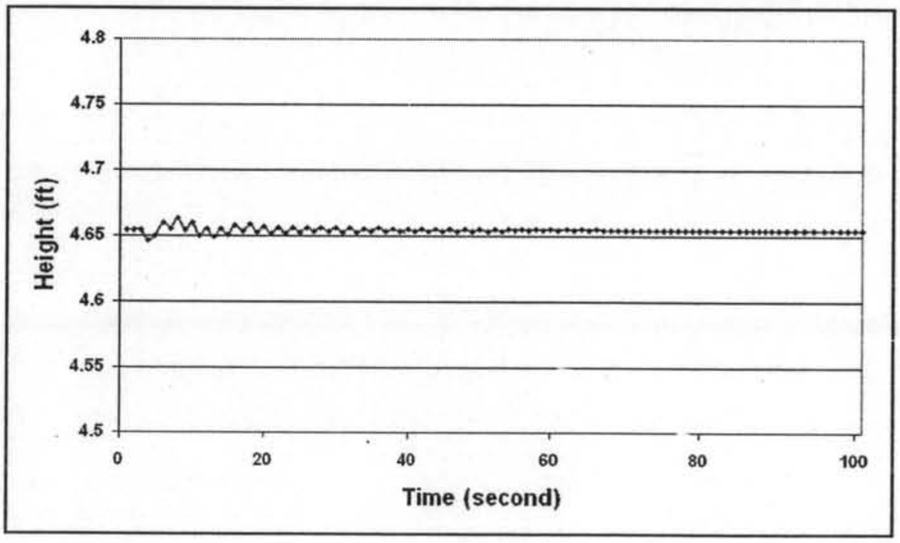

Figure 4.12 Response curve of controlled variable, height of liquid in tank, of cascade control of gravitational flow tank after the disturbance, input volumetric flowrate per tank area, changing from 0.311 to 0.35 ft/s. (Tuning parameters: K_{C1} = 0.200034 1/s^2, τ_{I1} =1 s, and τ_{D1} =0.25 s, K_{C2} =1.2 1/s^2, τ_{I2} = 1 s, and τ_{D2} = 0.25 s)

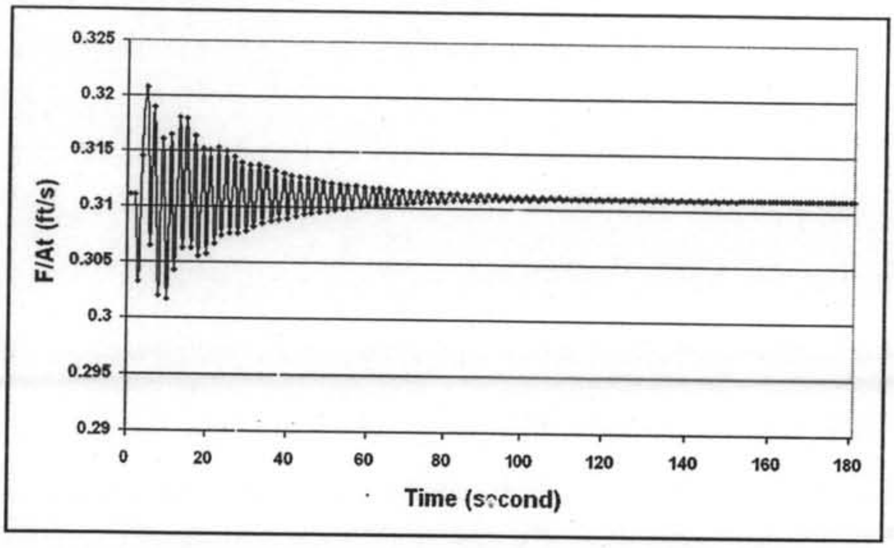

Figure 4.13 Response curve of manipulated variable, input volumetric flowrate per tank area (F/At), of cascade control of gravitational flow tank after the disturbance, input volumetric flowrate per tank area, changing from 0.311 to 0.35 ft/s. (Tuning parameters: K_{C1} = 0.200034 1/s^2, τ_{I1} =1 s, and τ_{D1} =0.25 s, K_{C2} =1.2 1/s^2, τ_{I2} = 1 s, and τ_{D2} = 0.25 s)

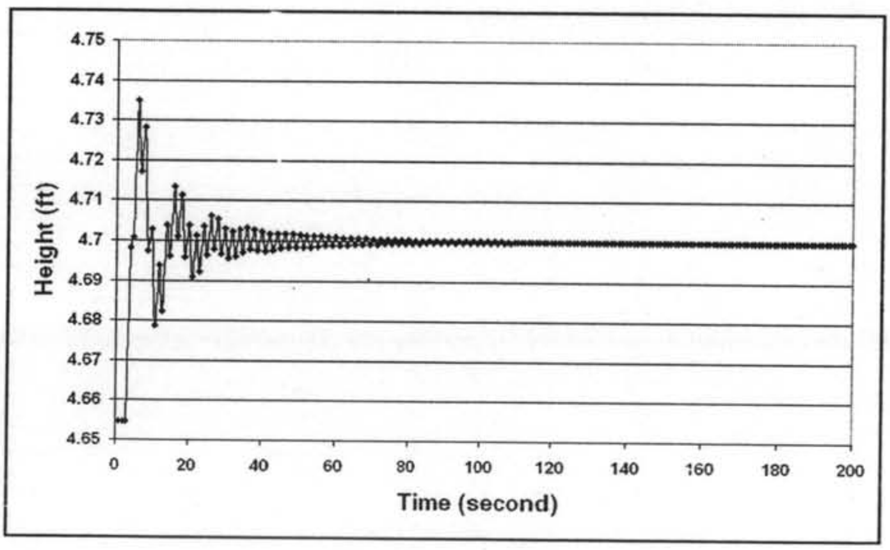

Figure 4.14 Response curve of controlled variable, height of liquid in tank, of cascade control of gravitational flow tank after setpoint of input volumetric flowrate per tank area changing from 4.6546 to 4.7 ft. (Tuning parameters: K_{C1} = 0.200034 1/s^2, τ_{I1} =1 s, and τ_{D1} =0.25 s, K_{C2} =1.2 1/s^2, τ_{I2} = 1 s, and τ_{D2} = 0.25 s)

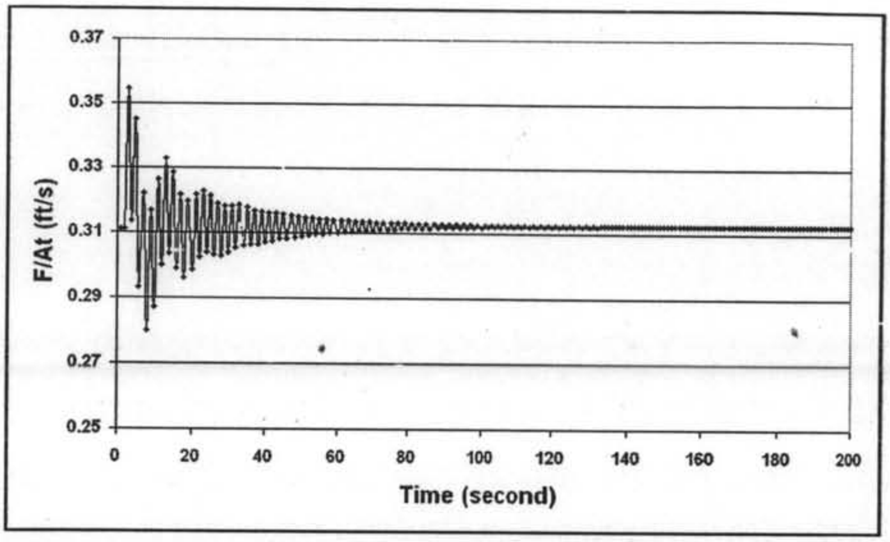

Figure 4.15 Response curve of manipulated variable, input volumetric flowrate per tank area (F/At), of cascade control of gravitational flow tank after setpoint of input volumetric flowrate per tank area, changing from 4.6546 to 4.7 ft. (Tuning parameters: K_{C1} = 0.200034 1/s^2, τ_{I1} =1 s, and τ_{D1} =0.25 s, K_{C2} =1.2 1/s^2, τ_{I2} = 1 s, and τ_{D2} = 0.25 s)

4.1.1.4 Dynamic Matrix Control

The control system illustrated in Figure 3.8 is operated by feeding process output information back to the controller. Dynamic matrix control uses the process output to predict the future output and to move the manipulated variable. The response curves of the dynamic matrix control on the gravitational flow tank are shown in Figures 4.16 to 4.19. The initial conditions are: input flowrate per tank area = 0.311 ft/s and height of water in the tank = 4.6546 ft. Figures 4.16 to 4.17 show the disturbance of the input volumetric flowrate per tank area changing from 0.311 to 0.35 ft/s. Figures 4.18 and 4.19 show the setpoint of the liquid height changing from 4.6546 to 4.7 ft. The IAE of the DMC with the disturbance is 22.03813 ft*s and the IAE of the controller with the setpoint change is 0.876235 ft*s when the setpoint changes. The weighting factor is 20; the number of NC is 40; and the number of NP is 80. The response curve of the step response is shown in Appendix G.

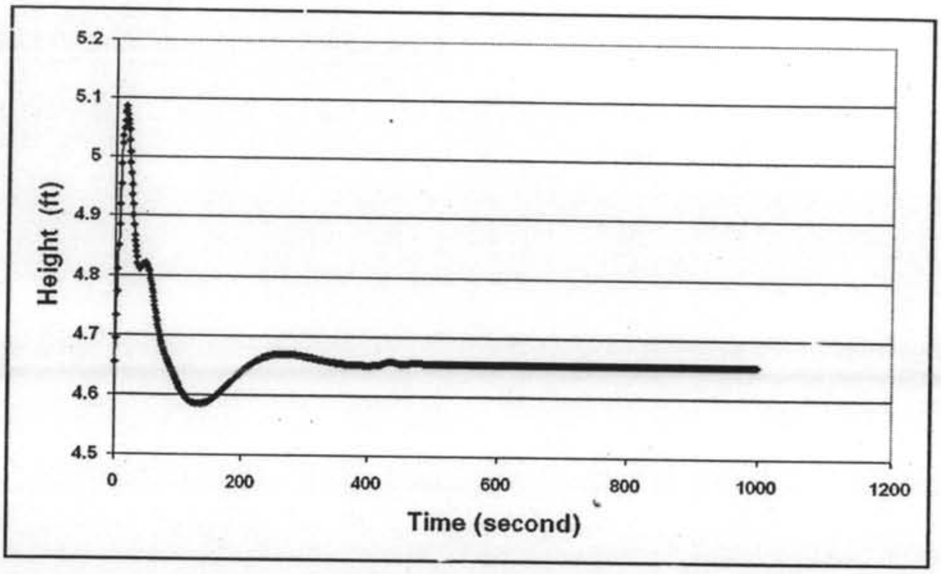

Figure 4.16 Response curve of controlled variable, height, of dynamic matrix control of gravitational flow tank with the disturbance of input volumetric flowrate per tank area changing from 0.311 to 0.35 ft/s. (Tuning parameters: f=20, NC=40, P=80)

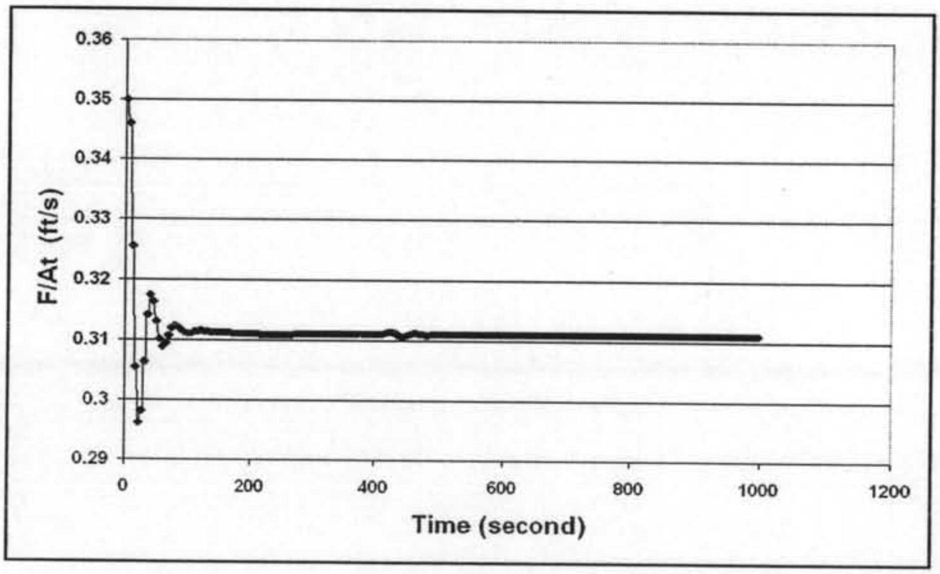

Figure 4.17 Response curve of manipulated variable, input volumetric flowrate per tank area (F/At), of dynamic matrix control of gravitational flow tank with the disturbance of input volumetric flowrate per tank area changing from 0.311 to 0. 35 ft/s. (Tuning parameters: f=20, NC=40, NP=80)

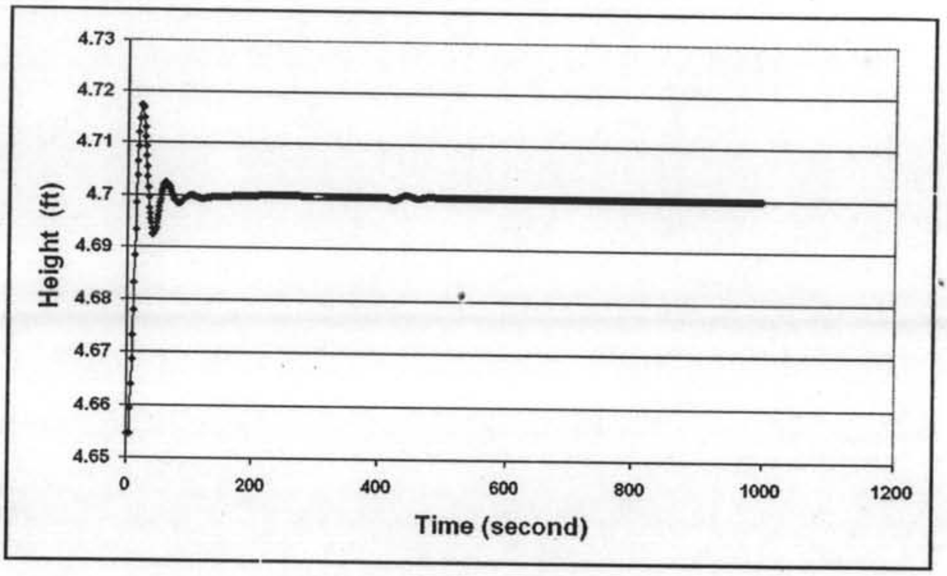

Figure 4.18 Response curve of controlled variable, height, of dynamic matrix control of gravitational flow tank with setpoint of height changing from 4.6546 to 4.7ft. (Tuning parameters: f=20, NC=40, NP=80)

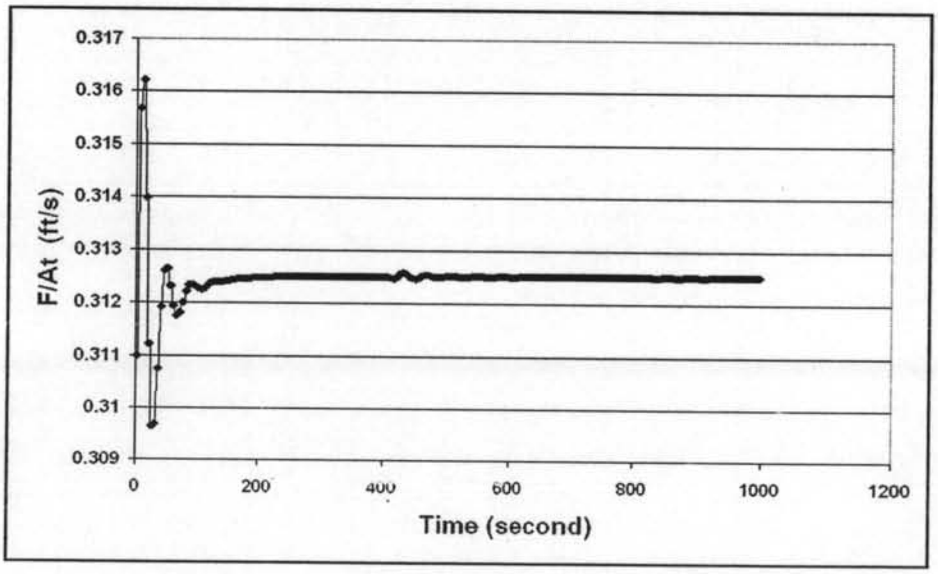

Figure 4.19 Response curve of manipulated variable, input volumetric flowrate per tank area (F/At), of dynamic matrix control of gravitational flow tank with the setpoint of height changing from 4.6546 to 4.7 ft. (Tuning parameters: f=20, NC=40, NP=80)

Table 4.1 IAE value of liquid level of gravitational flow tank

	IAE (ft*s)	
	Disturbance	Setpoint
Feedback	0.74885	1.07093
Cascade	0.11467	0.44013
DMC	22.03813	0.876235

From Table 4.1, the IAE values of the cascade control on the gravitational flow tank are the lowest because the cascade control has a secondary controller which reduces the effect of disturbance of feed, and the effect of the secondary controller gives higher proportional gain of the primary controller than the proportional gain of the feedback control. The IAE of the cascade control is the lowest value. For feedback and DMC, the IAE of the feedback with disturbance of input volumetric flowrate per tank area change shows that feedback gives less error than DMC. The IAE of the feedback with the setpoint change shows that DMC gives the error close to the feedback control.

4.1.2 Plug-flow Plus CSTR and Control System

The system in Figure 3.2 is the plug-flow plus CSTR. There are two parts of the control system, PID feedback control and dynamic matrix control.

4.1.2.1 Feedback Control

The structure of plug-flow plus CSTR with the PID feedback control is shown in Figure 4.20. The controller is used to control the concentration. The results of the feedback control on plug-flow plus CSTR are shown in Figures 4.21 to 4.24. Figures 4.21 and 4.22 show the disturbance of flowrate changing from 4 to 6 kmol/s and Figures 4.23 and 4.24 show the setpoint of concentration changing from 96.1337 to 18 kmol/m^3. The IAE of the concentration with the disturbance of feed flow change is 96.1337 kmol*s/m^3 and the IAE of the concentration with the setpoint change is 2476.307 kmol*s/m^3. The parameters used for adjusting the controller are K_C = 0.06312 m^3/s^2, τ_I = 31 s, and τ_D = 7.75 s by using Ziegler-Nichols's method. The tuning by Ziegler-Nichols's method gives K_u = 0.1052 $1/s^2$ and P_U = 62s. The result of tuning is shown in Appendix C.

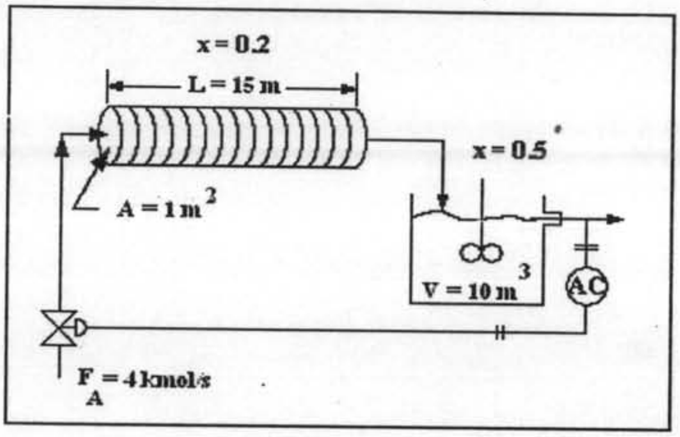

Figure 4.20 Plug-flow reactor plus CSTR with feedback control.

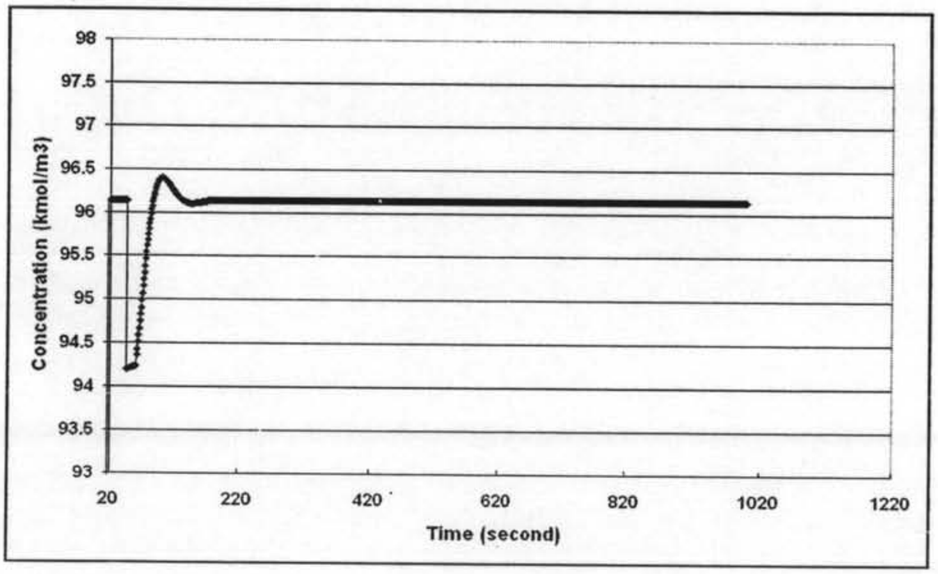

Figure 4.21 Response curve of feedback control on plug-flow plus CSTR of concentration (controlled variable) with the disturbance of flowrate changing from 4 to 6 kmol/s. (Tuning parameters: $K_C = 0.06312\ m^3/s^2$, τ_I = 31 s, and τ_D = 7.75 s)

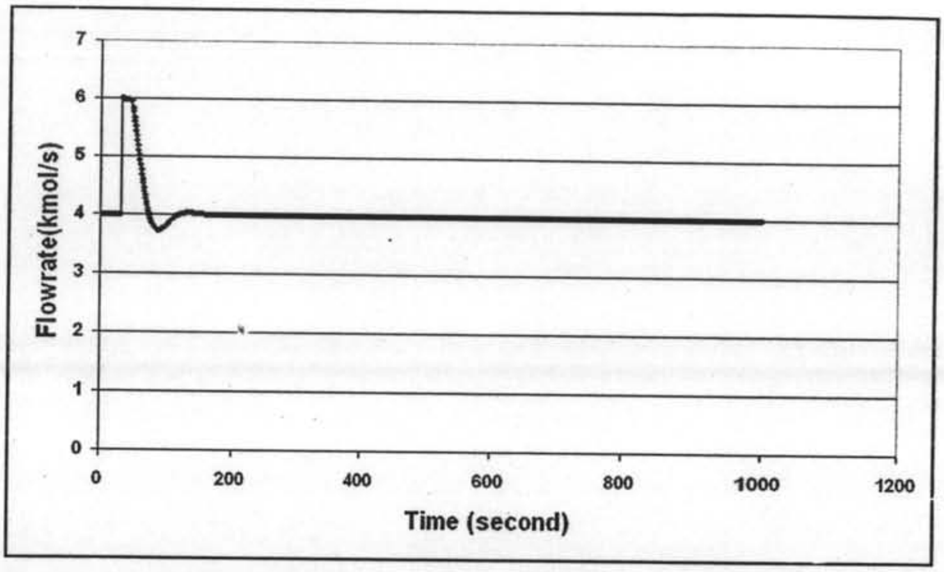

Figure 4.22 Response curve of feedback control on plug-flow plus CSTR of flowrate (manipulated variable) with the disturbance of flowrate changing from 4 to 6 kmol/s. (Tuning parameters: $K_C = 0.06312\ m^3/s^2$, $\tau_I = 31$ s, and $\tau_D = 7.75$ s)

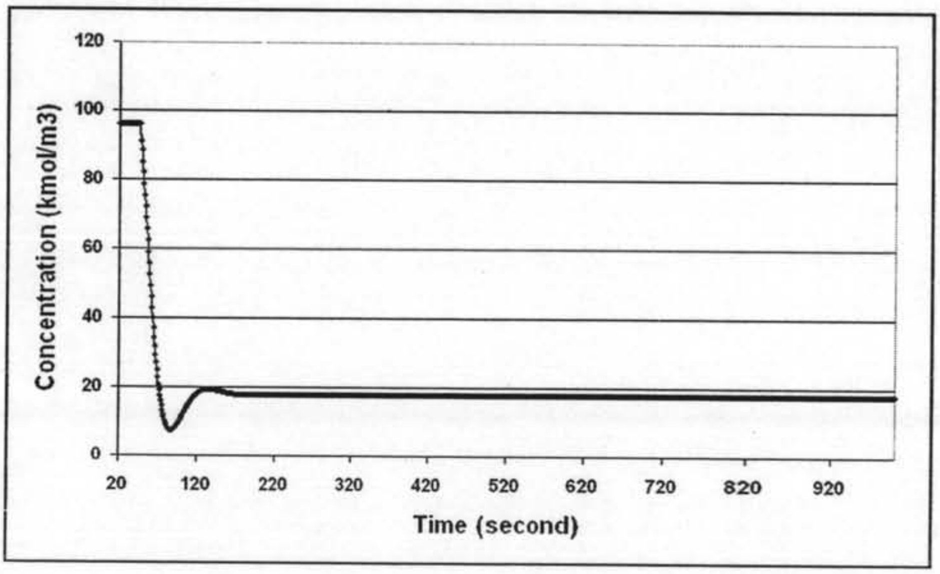

Figure 4.23 Response curve of feedback control on plug-flow plus CSTR of concentration (controlled variable) with the disturbance of setpoint changing from 96.1337 to 18 kmol/m3. (Tuning parameters: $K_C = 0.06312\ m^3/s^2$, $\tau_I = 31$ s, and $\tau_D = 7.75$ s)

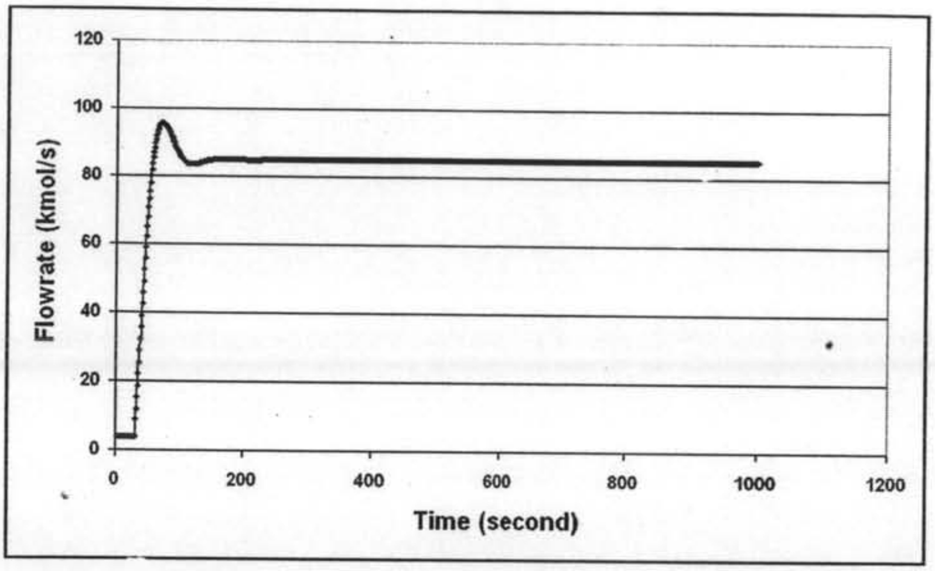

Figure 4.24 Response curve of feedback control on plug-flow plus CSTR of flowrate (manipulated variable) with the disturbance of setpoint changing from 96.1337 to 18 kmol/m3. (Tuning parameters: $K_C = 0.06312\ m^3/s^2$, $\tau_I = 31$ s, and $\tau_D = 7.75$ s)

4.1.2.2 Dynamic Matrix Control

The dynamic matrix control in the system is shown in Figure 4.25. The results of the DMC on plug-flow plus CSTR are shown in Figures 4.26 to 4.29. The IAE of the concentration with the disturbance of feed flow change is 78.72 kmol*s/m^3 and the IAE of the concentration with the setpoint change is 3241.89 kmol*s/m^3. The weighting factor is 40; the number of NC is 4; and the number of NP is 11. The response curve of the step response is shown in Appendix G.

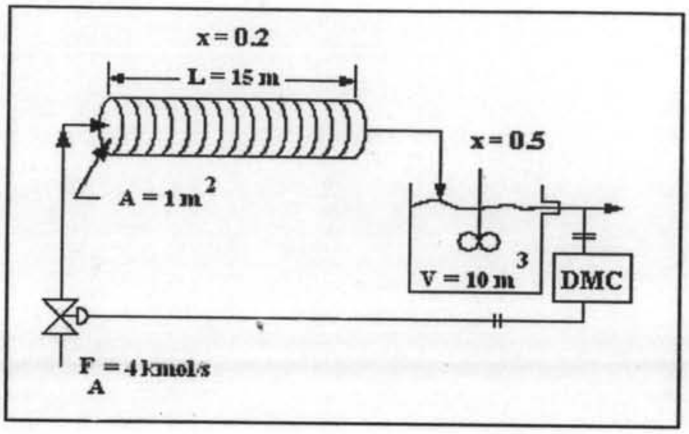

Figure 4.25 Plug-flow reactor plus CSTR with dynamic matrix control.

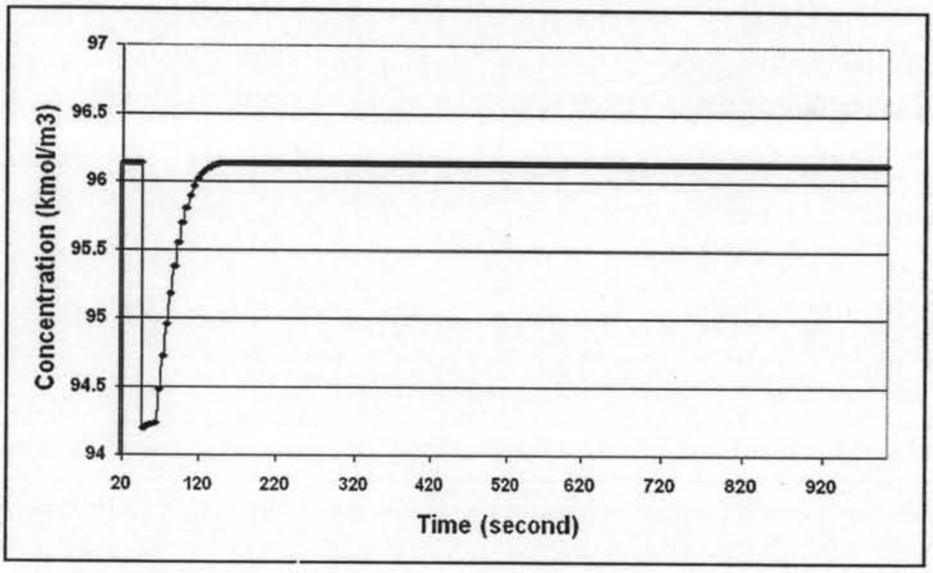

Figure 4.26 Response curve of DMC on plug-flow plus CSTR of concentration (controlled variable) with disturbance of flowrate changing from 4 to 6 kmol/s. (Tuning parameters: f=40, NC=4, NP=11)

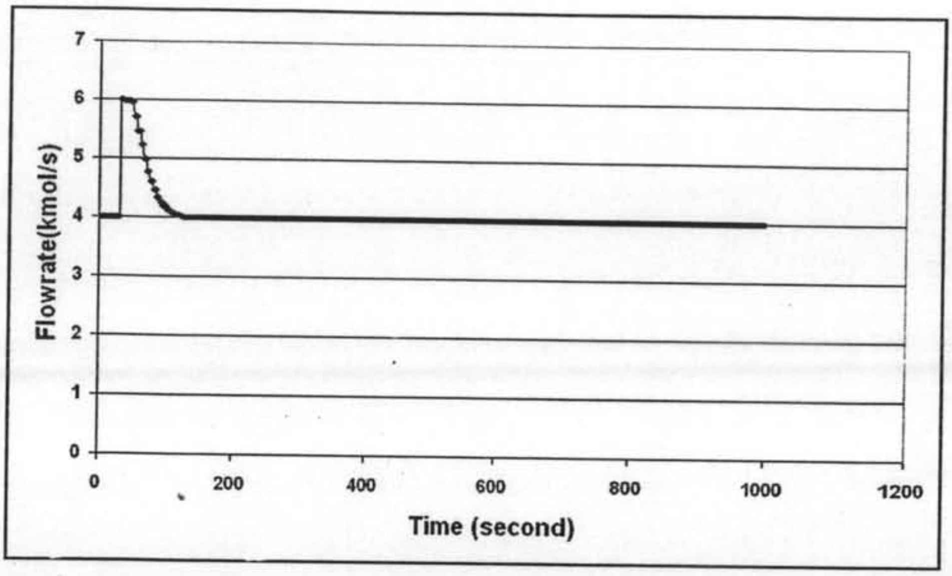

Figure 4.27 Response curve of DMC on plug-flow plus CSTR of flowrate (manipulated variable) with disturbance of flowrate changing from 4 to 6 kmol/s. (Tuning parameters: f=40, NC=4, NP=11)

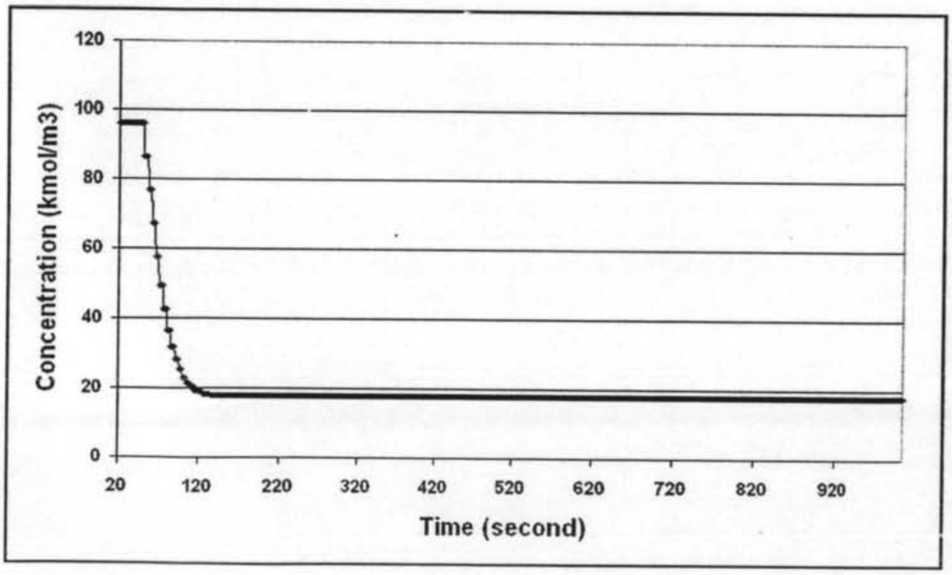

Figure 4.28 Response curve of DMC on plug-flow plus CSTR of concentration (controlled variable) with setpoint changing from 96.1337 to 18 kmol/m3. (Tuning parameters: f=40, NC=4, NP=11)

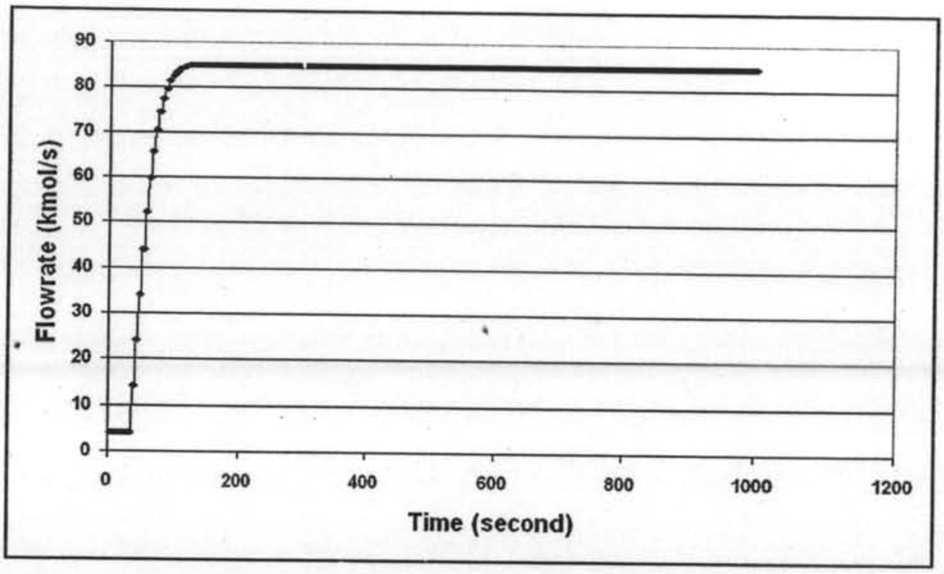

Figure 4.29 Response curve of DMC on plug-flow plus CSTR of flowrate (manipulated variable) with setpoint changing from 19.1337 to 18 kmol/m3. (Tuning parameters: f=40, NC=4, NP=11)

The effects of the weighting factor on concentration are shown in Figure 4.30. The small weighting factor, f, gives the oscillation and overshoot but the large value of the weighting factor gives slow action to set the controlled variable to the setpoint, and less oscillation.

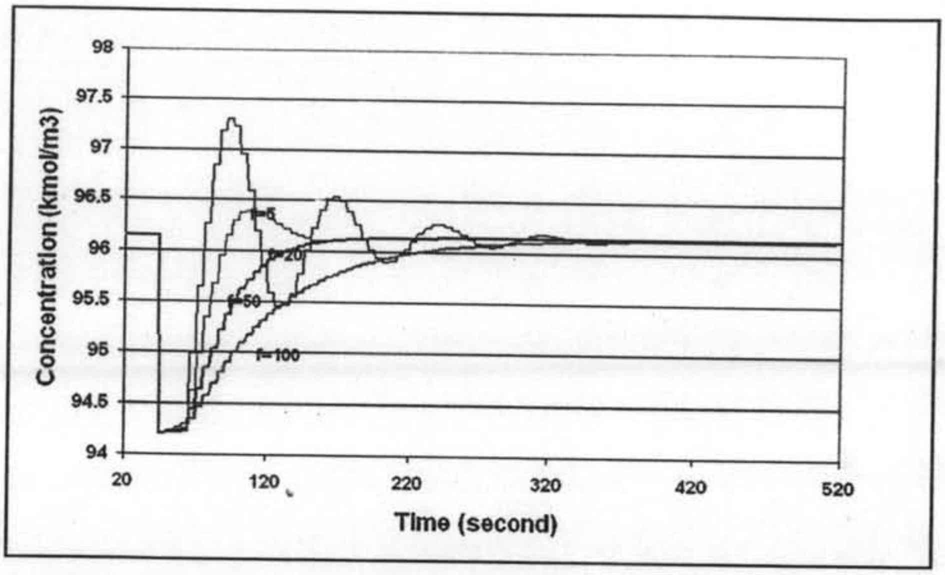

Figure 4.30 Response curve of DMC on plug-flow plus CSTR of concentration (controlled variable) with disturbance of flowrate changing from 4 to 6 kmol/s.

From Table 4.2, the DMC gives less error and faster than the feedback control in the case of the disturbance of feed flowrate change. The DMC gives larger error and slower than the feedback control in the case of the setpoint of concentration change but the response curves showed that the DMC gives lower overshoot than the feedback control.

Table 4.2 IAE value of liquid level of plug-flow plus CSTR

	IAE (kmol*s/m^3)	
	Disturbance	Setpoint
Feedback	96.1337	2476.31
DMC	78.722803	3241.89

4.1.3 Binary Distillation Model without Control System

A dynamic distillation column without the control system is simulated by using the implicit Euler method with the Digital Visual Fortran program. There are 30 stages for the column. The first stage contains a total condenser and reflux drum and the last stage is a reboiler. The number of trays of the column including the reboiler and the condenser is 30. The reflux ratio, R, is 2.90, and the feed flowrate is at 0.09 kg-mol/minute. The feed is a mixture of propane and butane composition at a ratio of 0.5:0.5 (propane: butane). The feed enters at tray no.15 with a pressure of 17 bars and a temperature of 369 K. The product specifications of mole fraction are 0.9981 for propane at the top and 0.9925 for butane at the bottom. The pressure drop of the column is assumed constant at 0.065 bars. The pressure in the reflux drum is equal to 16 bars. The compositions at the steady state condition of liquid and vapor are shown in Table 4.3 and Figure 4.31.

The calculation method of the column model is from IFP-school, as shown in Appendix A.

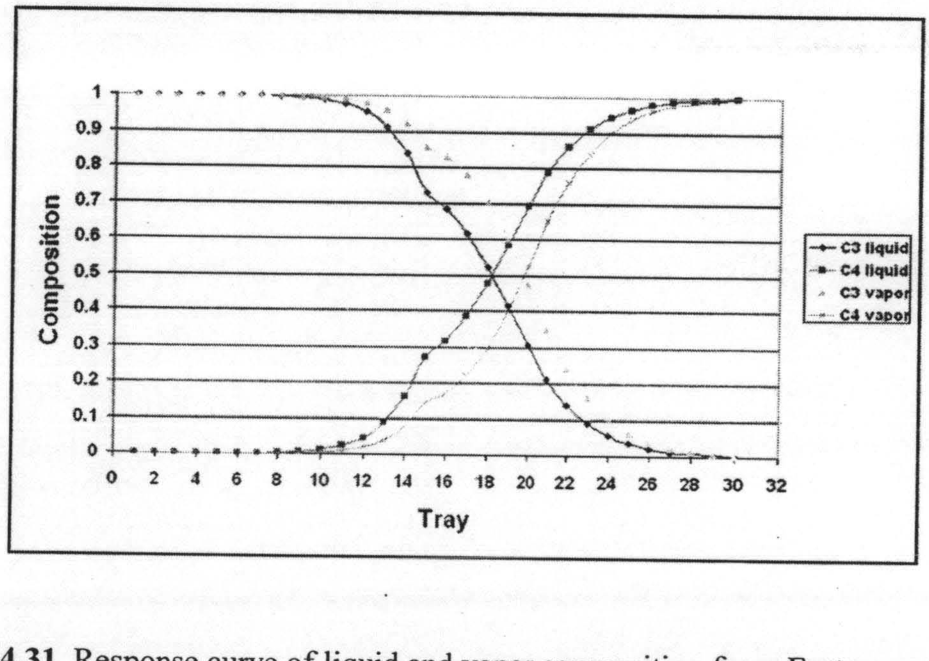

Figure 4.31 Response curve of liquid and vapor composition from Fortran program.

Table 4.3 Vapor and liquid composition from Fortran program at steady state condition

Tray No.	Vapor		Liquid	
	Propane	Butane	Propane	Butane
1	1	0	1	0
2	1	0	1	0
3	1	0	0.9999	0.0001
4	0.9999	0.0001	0.9999	0.0001
5	0.9999	0.0001	0.9997	0.0003
6	0.9998	0.0002	0.9994	0.0006
7	0.9995	0.0005	0.9988	0.0012
8	0.9989	0.0011	0.9974	0.0026
9	0.9977	0.0023	0.9947	0.0053
10	0.9953	0.0047	0.989	0.011
11	0.9903	0.0097	0.9775	0.0225
12	0.9801	0.0199	0.9547	0.0453
13	0.96	0.04	0.9117	0.0883
14	0.9223	0.0777	0.8376	0.1624
15	0.8579	0.1421	0.7274	0.2726
16	0.8284	0.1716	0.6828	0.3172
17	0.7793	0.2207	0.6147	0.3853
18	0.7035	0.2965	0.5224	0.4776
19	0.5993	0.4007	0.4142	0.5858
20	0.4754	0.5246	0.306	0.694
21	0.3505	0.6495	0.2123	0.7877
22	0.2424	0.7576	0.1404	0.8596
23	0.1598	0.8402	0.0898	0.9102
24	0.1019	0.8981	0.0562	0.9438
25	0.0636	0.9364	0.0346	0.9654
26	0.039	0.961	0.0211	0.9789
27	0.0237	0.9763	0.0128	0.9872
28	0.0142	0.9858	0.0076	0.9924
29	0.0083	0.9917	0.0045	0.9955
30	0.0047	0.9953	0.0025	0.9975

4.1.4 Distillation Column with PID Cascade Control

The distillation column without the control system is simulated using IFP's method, as shown in Appendix A. The PID cascade controllers are used for controlling tray temperature and the levels of the reflux drum and the bottom column, as shown in Figure 4.32. This type of controller is applied to the distillation column for controlling column compositions. The cascade controllers are composed of the primary and secondary controllers. The first cascade controller controls the temperature of tray no.6 and the second one controls the temperature of tray no.25.

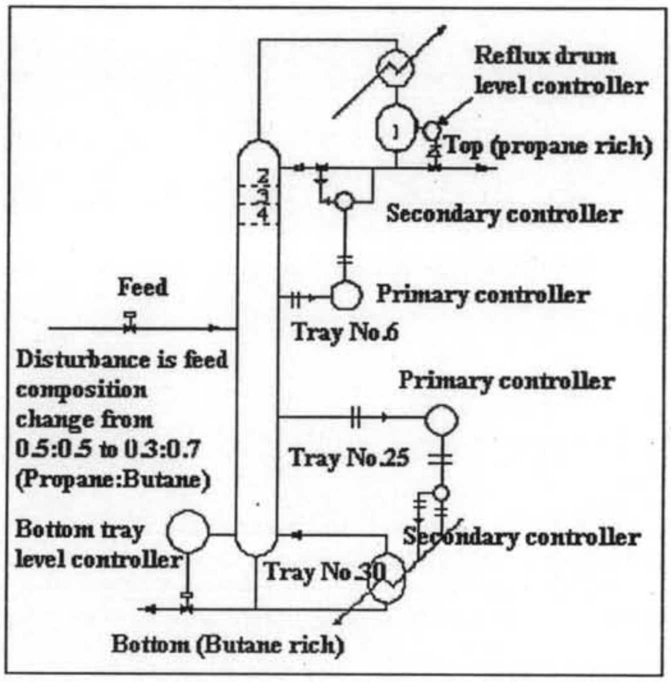

Figure 4.32 Binary distillation column with cascade controller.

4.1.4.1 Disturbance of Changing Feed Composition

The results of the cascade control for the temperature at tray no.6 with the disturbance of changing feed composition from 0.5:0.5 to 0.3:0.7 are shown in Figures 4.33 and 4.34. The response curves of the cascade controls have an oscillation. The tuning parameter is shown in Table 4.4 and the response curve of tuning is shown in Appendix C.

Table 4.4 Tuning parameters for cascade control of depropanizer column

Controller		K_{CU}	Pu	K_C	τ_i	τ_d
reflux (flowrate control)		2 (1/s)	2 (s)	1.2 (1/s)	1 (s)	0.25 (s)
steam (flowrate control)		2 (1/s)	2 (s)	1.2 (1/s)	1 (s)	0.25 (s)
reflux drum (level control)		15 $1/(m^*(s)^2)$	18 (s)	9 $1/(m^*(s)^2)$	9 (s)	2.25 (s)
bottom column (level control)		15 $1/(m^*(s)^2)$	17 (s)	9 $1/(m^*(s)^2)$	8.5 (s)	2.125 (s)
Cascade Tuning	tray no.6 (temperature control)	0.00002 $1/(K^*(min)^2)$	512 (min)	0.000012 $1/(K^*(min)^2)$	256 (min)	64 (min)
	tray no.25 (temperature control)	0.00001 $1/(K^*(min)^2)$	604 (min)	0.000006 $1/(K^*(min)^2)$	302 (min)	75.5 (min)

where

K_{CU} is the ultimate gain for reflux and stem (1/s), reflux drum and bottom column $(1/(m^*(s)^2))$, and temperature control at tray no.6 and no.25 $(1/(K^*(min)^2))$.

P_U is the ultimate period for reflux, stem, reflux drum, and bottom column (s), and temperature control at tray no.6 and no.25 (min).

K_C is the controller gain for reflux and stem (1/s), reflux drum and bottom column $(1/(m^*(s)^2))$, and temperature control at tray no.6 and no.25 $(1/(K^*(min)^2))$.

τ_i is the integral time for reflux, stem, reflux drum, and bottom column (s), and temperature control at tray no.6 and no.25 (min).

τ_D is the derivative time for reflux, stem, reflux drum, and bottom column (s), and temperature control at tray no.6 and no.25 (min).

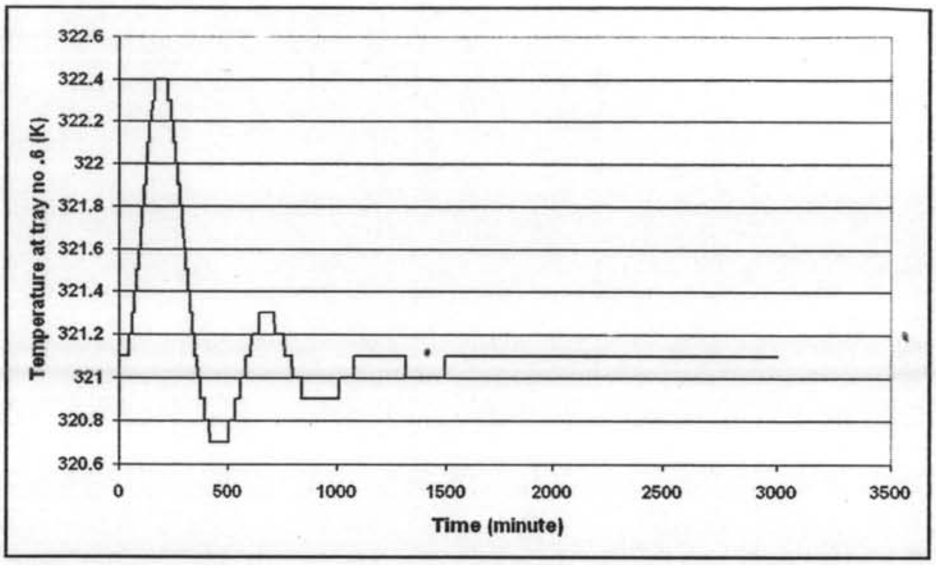

Figure 4.33 Response curve of temperature (controlled variable) of cascade control of temperature of tray no.6 with disturbance of changing feed composition from 0.5:0.5 to 0.3:0.7 (propane:butane).

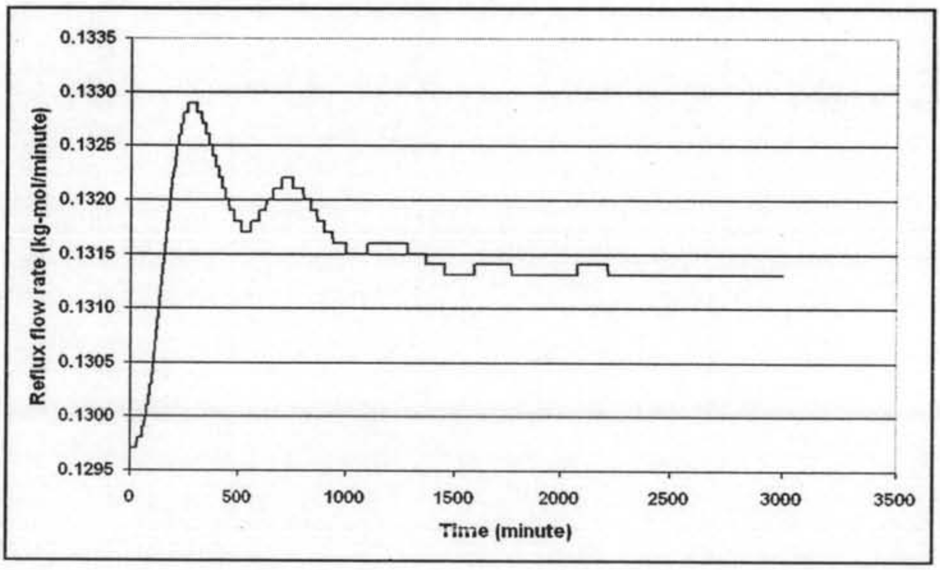

Figure 4.34 Response curve of reflux flowrate (manipulated variable) of cascade control of temperature of tray no.6 with disturbance of changing feed composition from 0.5:0.5 to 0.3:0.7 (propane:butane).

The results of the cascade control for temperature at tray no.25 with the disturbance of changing feed composition from 0.5:0.5 to 0.3:0.7 are shown in Figures 4.35 and 4.36. The response curves of the cascade controls have an oscillation.

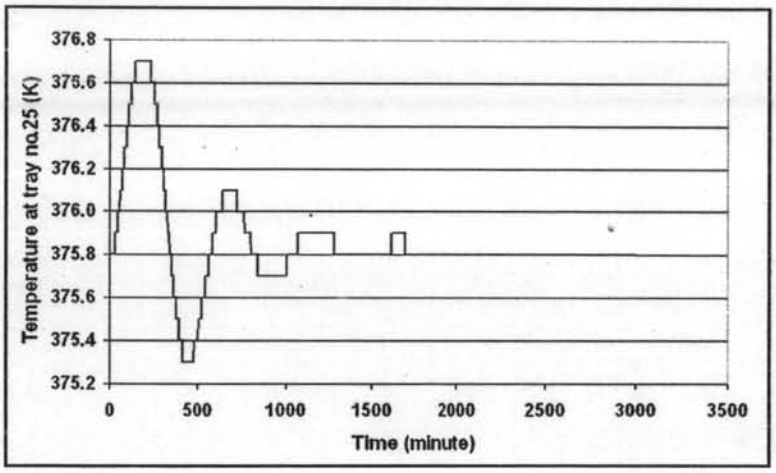

Figure 4.35 Response curve of temperature (controlled variable) of cascade control of temperature of tray no.25 with disturbance of changing feed composition from 0.5:0.5 to 0.3:0.7 (propane:butane).

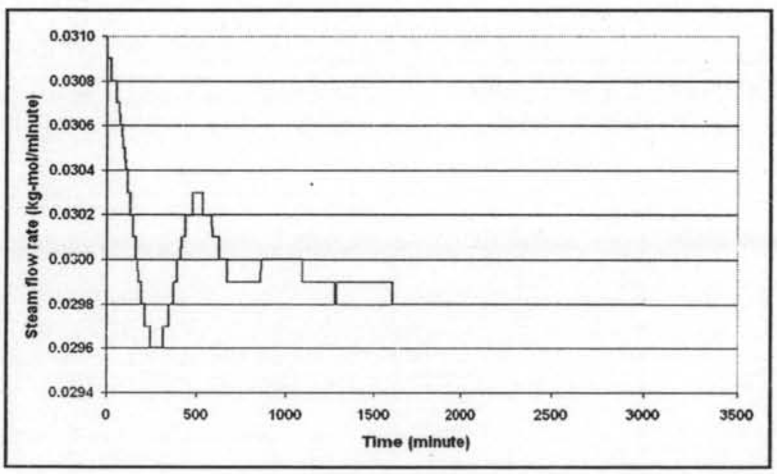

Figure 4.36 Response curve of steam flowrate (manipulated variable) of cascade control of temperature of tray no.25 with disturbance of changing feed composition from 0.5:0.5 to 0.3:0.7 (propane:butane).

4.1.4.2 Disturbance of Changing Feed Flowrate

The results of the cascade control for temperature at tray no.6 with the disturbance of changing feed flowrate 0.09 to 0.1 (kg-mol/minute) are shown in Figures 4.37 and 4.38. The response curves of the cascade controls have few oscillation.

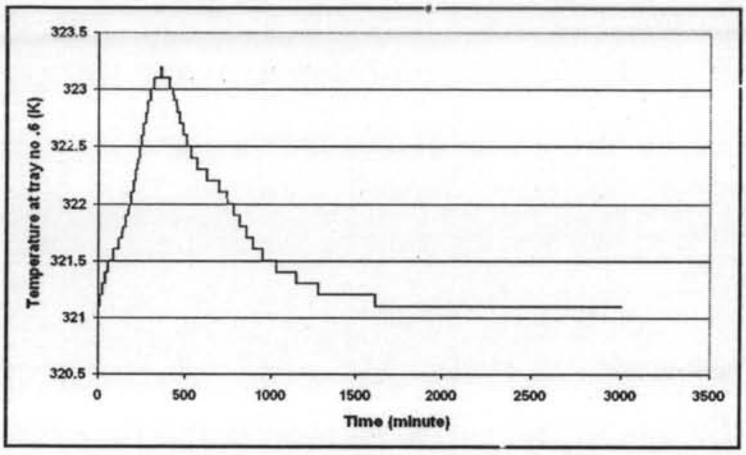

Figure 4.37 Response curve of temperature (controlled variable) of cascade control of temperature of tray no.6 with disturbance of changing feed flowrate from 0.09 to 0.1 (kg-mol/minute).

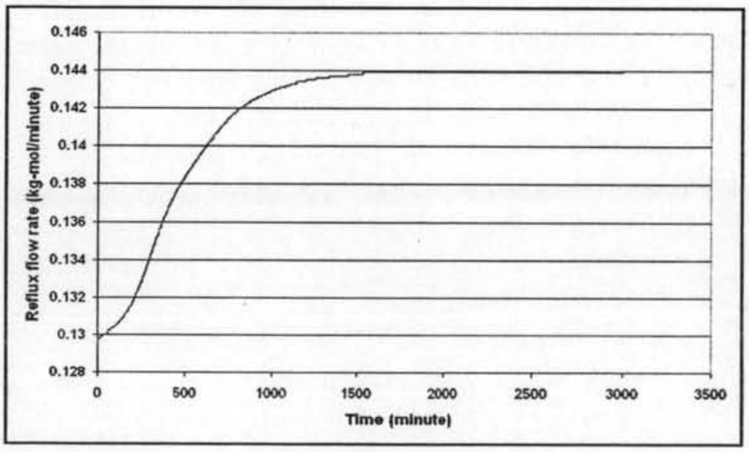

Figure 4.38 Response curve of reflux flowrate (manipulated variable) of cascade control of temperature of tray no.6 with disturbance of changing feed flowrate from 0.09 to 0.1 (kg-mol/minute).

The results of the cascade control for temperature at tray no.25 with the disturbance of changing feed flowrate 0.09 to 0.1 (kg-mol/minute) are shown in Figures 4.39 and 4.40. The response curves of the cascade controls have few oscillation.

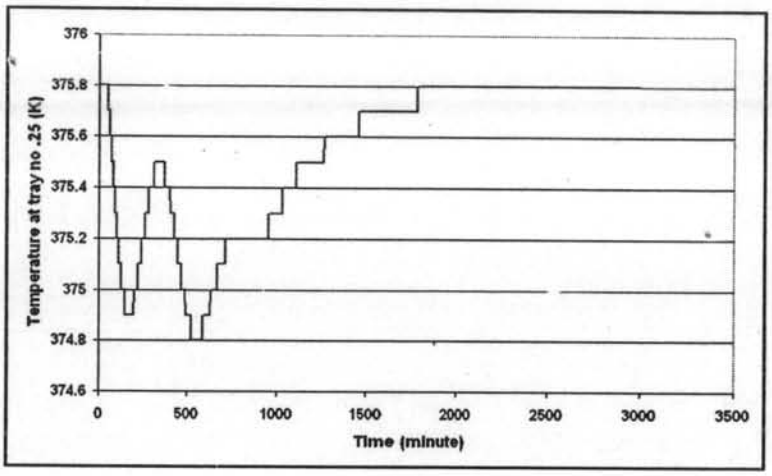

Figure 4.39 Response curve of temperature (controlled variable) of cascade control of temperature of tray no.25 with disturbance of changing feed flowrate from 0.09 to 0.1 (kg-mol/minute).

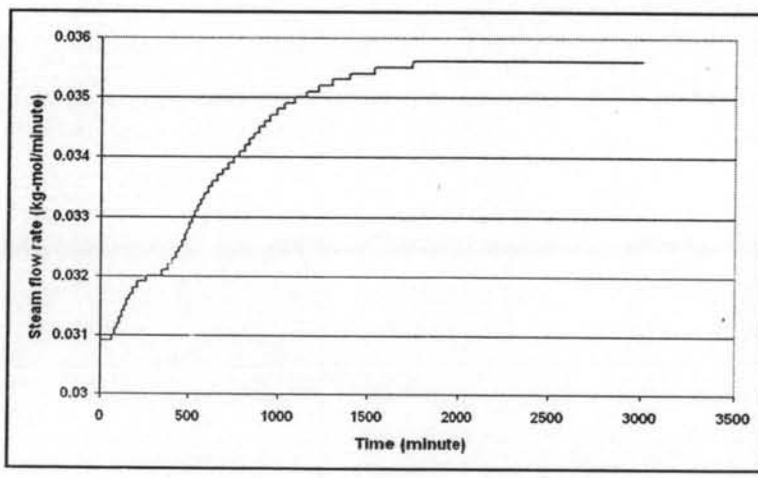

Figure 4.40 Response curve of steam flowrate (manipulated variable) of two point cascade control of temperature of tray no.25 with disturbance of changing feed flowrate from 0.09 to 0.1 (kg-mol/minute).

4.1.4.3 Disturbance of Changing Setpoint Tray No.6

The results of the cascade control for temperature at tray no.6 with disturbance of changing setpoint of tray no.6 from 321.1 to 323.3 (K) are shown in Figures 4.41 and 4.42. The response curves of the cascade controls have few oscillation and low overshoot.

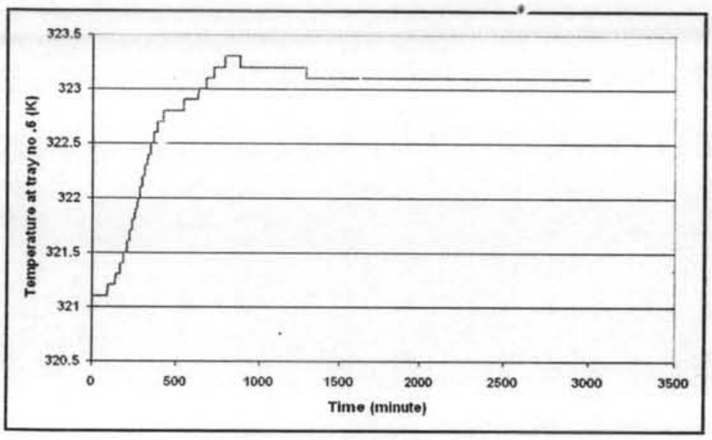

Figure 4.41 Response curve of temperature (controlled variable) of cascade control of temperature of tray no.6 with disturbance of changing setpoint of tray no.6 from 321.1 to 323.1 (K).

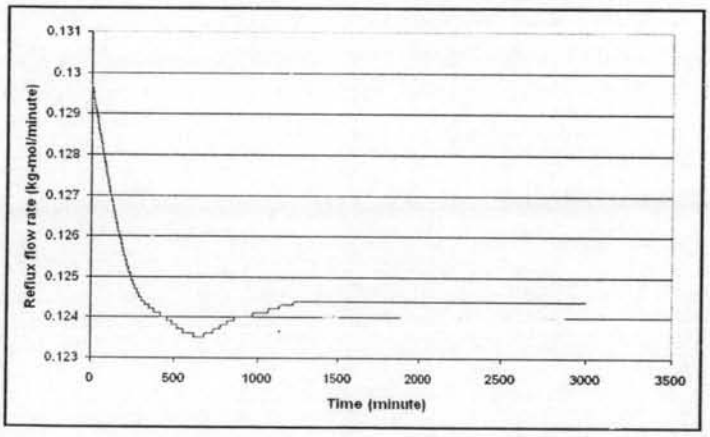

Figure 4.42 Response curve of reflux flowrate (manipulated variable) of cascade control of temperature of tray no.6 with disturbance of changing setpoint of tray no.6 from 321.1 to 323.1 (K).

The results of the cascade control for temperature at tray no.25 with disturbance of changing setpoint of tray no.6 from 321.1 to 323.3 (K) are shown in Figures 4.43 and 4.44. The response curves of the cascade controls have few oscillation and low overshoot.

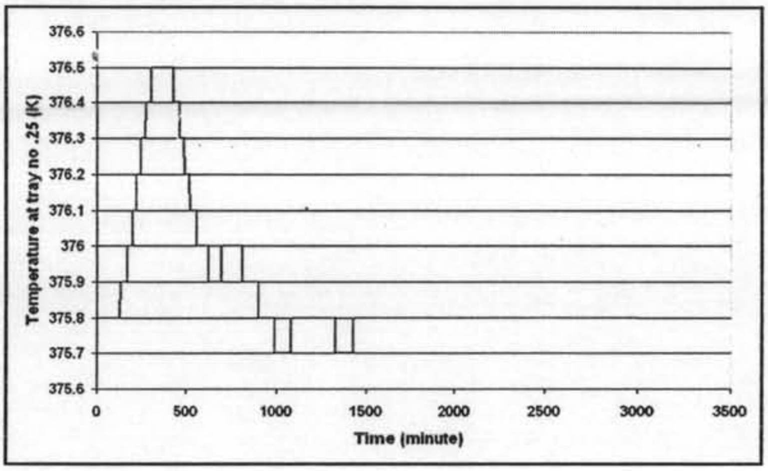

Figure 4.43 Response curve of temperature (controlled variable) of cascade control of temperature of tray no.25 with disturbance of changing setpoint of tray no.6 from 321.1 to 323.1 (K).

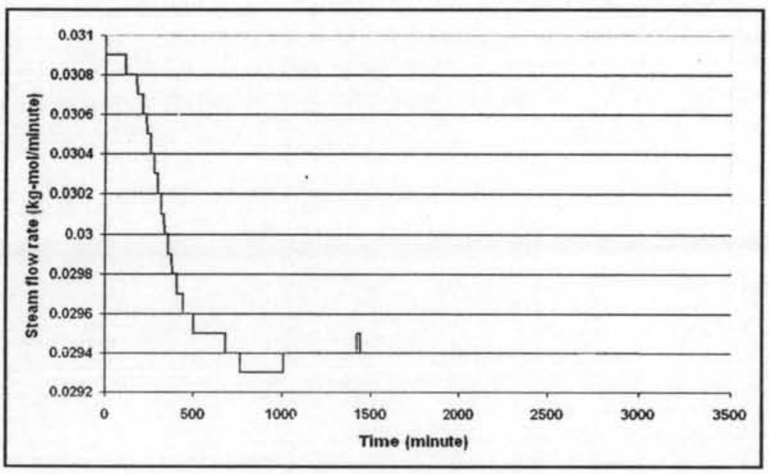

Figure 4.44 Response curve of steam flowrate (manipulated variable) of cascade control of temperature of tray no.25 with disturbance of changing setpoint of tray no.6 from 321.1 to 323.1 (K).

4.1.4.4 Disturbance of Changing Steam Flowrate

The results of the cascade control for temperature at tray no.6 with disturbance of changing steam flowrate from 0.0309 to 0.02 (kg-mol/minute) are shown in Figures 4.45 and 4.46. The response curves of the controlled variable from cascade control do not change.

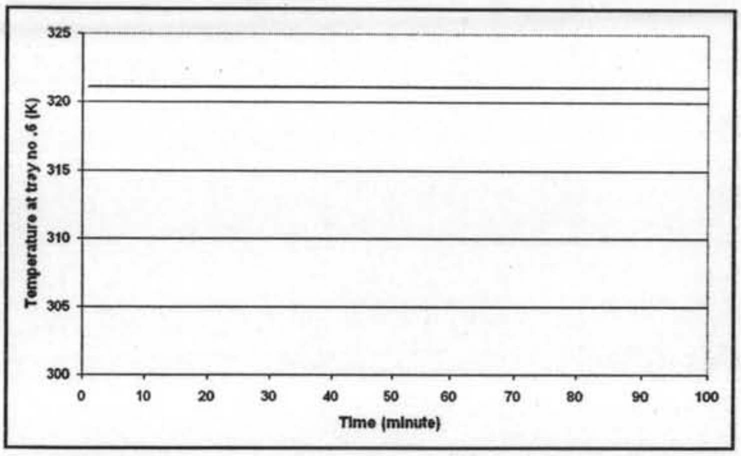

Figure 4.45 Response curve of temperature (controlled variable) of cascade control of temperature of tray no.6 with disturbance of changing steam flowrate from 0.0309 to 0.02 (kg-mol/minute).

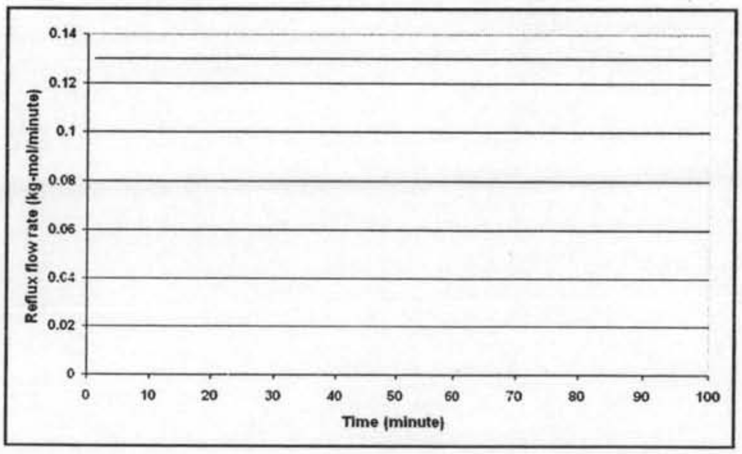

Figure 4.46 Response curve of reflux flowrate (manipulated variable) of cascade control of temperature of tray no.6 disturbance of changing steam flowrate from 0.0309 to 0.02 (kg-mol/minute).

The results of the cascade control for temperature at tray no.25 with disturbance of changing steam flowrate from 0.0309 to 0.02 (kg-mol/minute) are shown in Figures 4.47 and 4.48. The response curves of the controlled variable from the cascade control do not change because the secondary controller has quickly eliminated the effect of steam change.

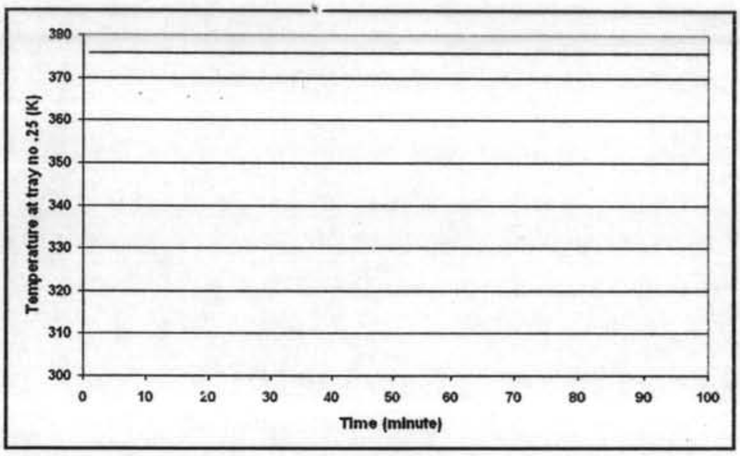

Figure 4.47 Response curve of temperature (controlled variable) of cascade control of temperature of tray no.25 with disturbance of changing steam flowrate from 0.0309 to 0.02 (kg-mol/minute).

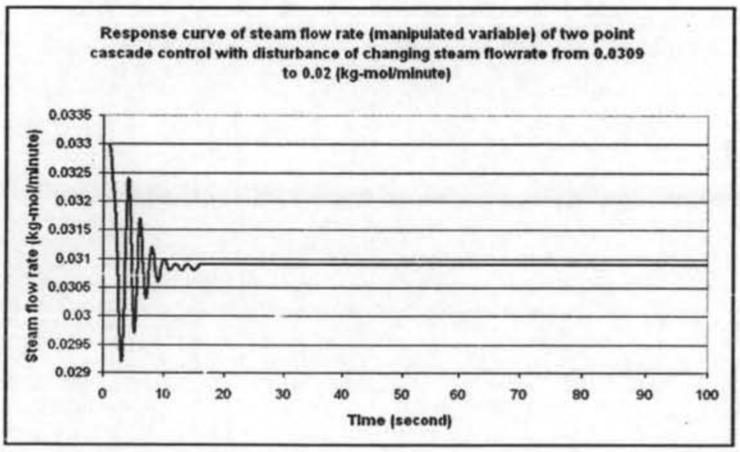

Figure 4.48 Response curve of steam flowrate (manipulated variable) of cascade control of temperature of tray no.25 with disturbance of changing steam flowrate from 0.0309 to 0.02 (kg-mol/minute).

4.1.5 Distillation Column with Dynamic Matrix Control (DMC)

The distillation column with the DMC for temperature of tray no. 6 and tray no. 25 is shown in Figure 4.49. Two dynamic matrix controls are applied to the depropanizer column. One DMC (DMC1) is used to control the temperature of tray no.6 and another (DMC2) is used to control the temperature of tray no.25.

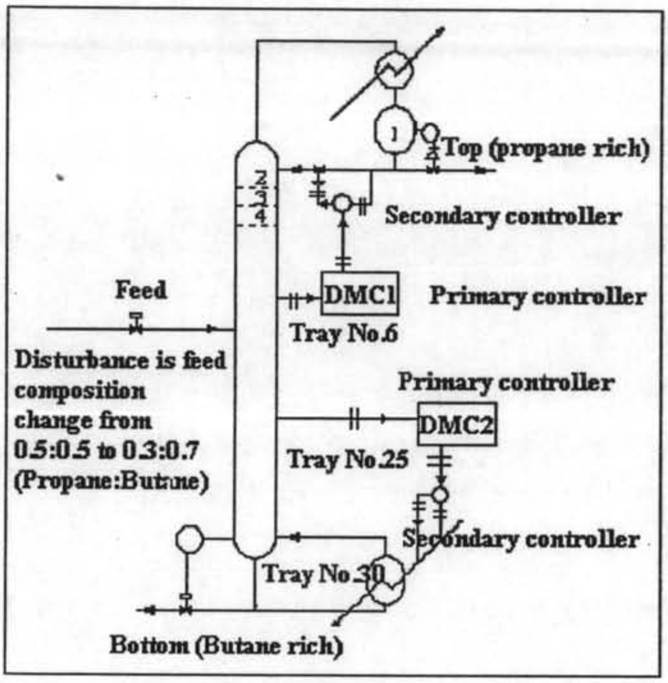

Figure 4.49 Binary distillation column with dynamic matrix control.

4.1.5.1 Disturbance of Changing Feed Composition

The results of the DMC of temperature of tray no.6 with the disturbance of changing feed composition from 0.5:0.5 to 0.3:0.7 are shown in Figures 4.50 and 4.51. The response curves of the controlled variable show few oscillations before reaching the setpoint. The tuning parameters are shown in Table 4.5 and the response curves of the step change are shown in Appendix G.

Table 4.5 Tuning parameters for DMC of depropanizer column

Controller		K_{CU}	Pu	K_C	τ_i	τ_d
reflux (flowrate control)		2 (1/s)	2 (s)	1.2 (1/s)	1 (s)	0.25 (s)
steam (flowrate control)		2 (1/s)	2 (s)	1.2 (1/s)	1 (s)	0.25 (s)
reflux drum (level control)		15 $1/(m^*(s)^2)$	18 (s)	9 $1/(m^*(s)^2)$	9 (s)	2.25 (s)
bottom column (level control)		15 $1/(m^*(s)^2)$	17 (s)	9 $1/(m^*(s)^2)$	8.5 (s)	2.125 (s)
			NC	NP	f	
DMC tuning	DMC1 (temperature at tray no.6control)		150	521	1^*10^8	
	DMC2 (temperature at tray no.25 control)		150	692	1^*10^7	

where

K_{CU} is the ultimate gain for reflux and stem (1/s), reflux drum and bottom column ($1/(m^*(s)^2)$), and temperature control at tray no.6 and no.25 ($1/(K^*(min)^2)$).

P_U is the ultimate period for reflux, stem, reflux drum, and bottom column (s), and temperature control at tray no.6 and no.25 (min).

K_C is the controller gain for reflux and stem (1/s), reflux drum and bottom column ($1/(m^*(s)^2)$), and temperature control at tray no.6 and no.25 ($1/(K^*(min)^2)$).

τ_i is the integral time for reflux, stem, reflux drum, and bottom column (s), and temperature control at tray no.6 and no.25 (min).

τ_D is the derivative time for reflux, stem, reflux drum, and bottom column (s), and temperature control at tray no.6 and no.25 (min).

NC is the number of the time interval of the manipulated variable moves in the future.

NP is the number of the time interval of the controlled variable change that covers 90 to 95 % of the system response.

f is the weighting factor preventing large changes in manipulated variable.

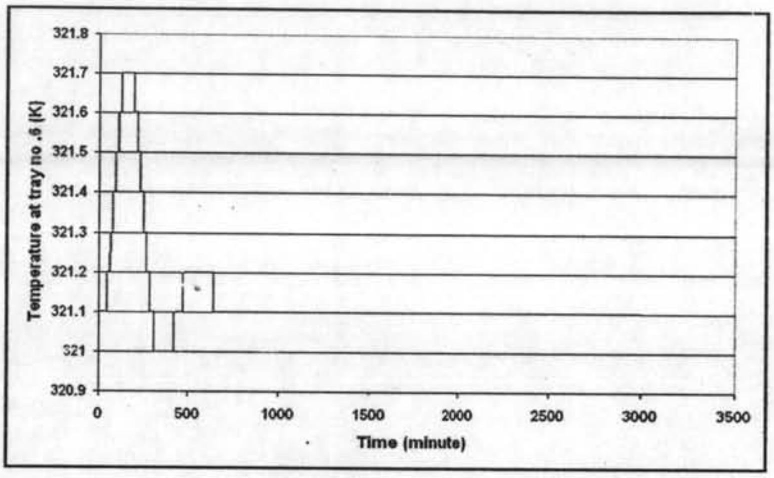

Figure 4.50 Response curve of temperature (controlled variable) of tray no.6 of dynamic matrix control with disturbance of changing feed composition from 0.5:0.5 to 0.3:0.7 (propane:butane).

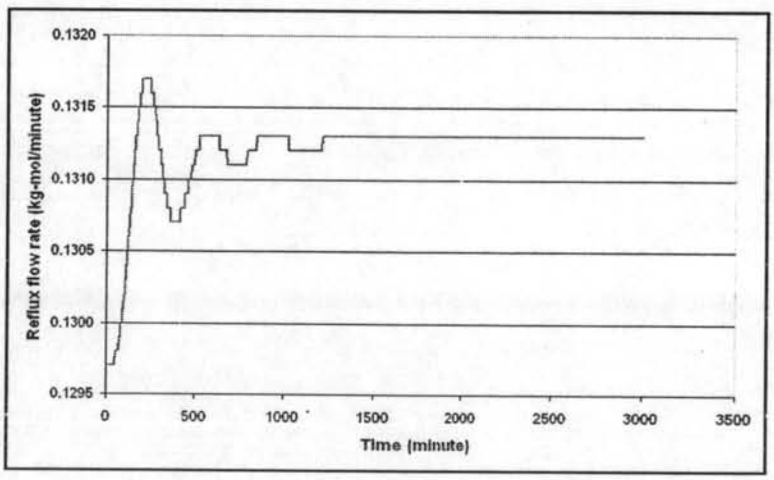

Figure 4.51 Response curve of reflux flowrate (manipulated variable) of dynamic matrix control of temperature of tray no.6 with disturbance of changing feed composition from 0.5:0.5 to 0.3:0.7 (propane:butane).

The results of the dynamic matrix control of temperature of tray no.25 with the disturbance of changing feed composition from 0.5:0.5 to 0.3:0.7 are shown in Figures 4.52 and 4.53. The response curves of the controlled variable are few oscillations before reaching the setpoint.

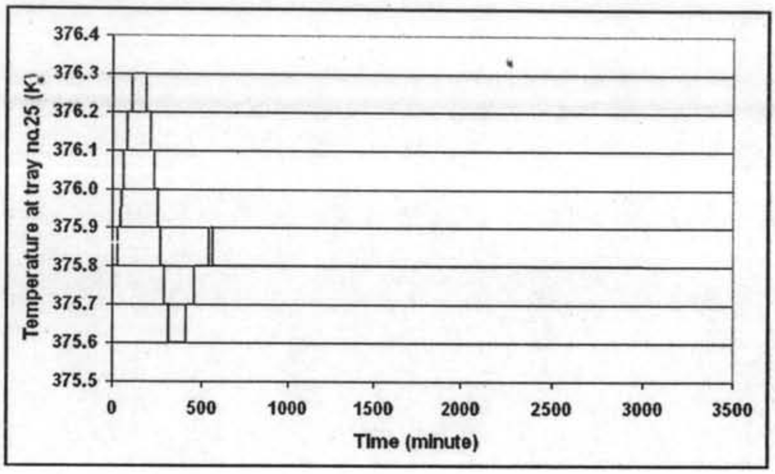

Figure 4.52 Response curve of temperature (controlled variable) of tray no.25 of dynamic matrix control with disturbance of changing feed composition from 0.5:0.5 to 0.3:0.7 (propane:butane).

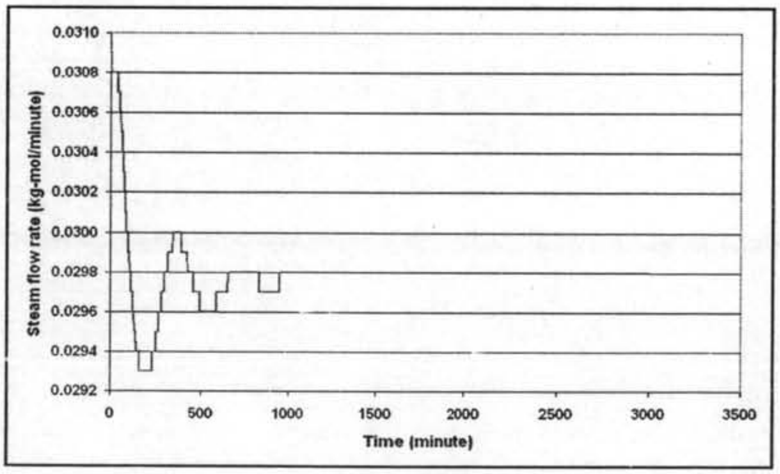

Figure 4.53 Response curve of steam flowrate (manipulated variable) of dynamic matrix control with disturbance of changing feed composition from 0.5:0.5 to 0.3:0.7 (propane:butane).

Table 4.6 IAE value of temperature of trays no.6 and no.25 with disturbance of changing feed composition from 0.5:0.5 to 0.3:0.7 (propane:butane)

Tray No.	IAE(K*min.)	
	Cascade	DMC
6	388	120
25	349	111

From Table 4.6, the IAE values show that the DMC is a faster control system than the cascade control system in reducing the error of controlled variable.

4.1.5.2 Disturbance of Changing Feed Flowrate

The results of the DMC of temperature of tray no.6 with the disturbance of changing feed flowrate from 0.09 to 0.1 (kg-mol/minute) are shown in Figures 4.54 and 4.55. The response curves of the controlled variable have no oscillation.

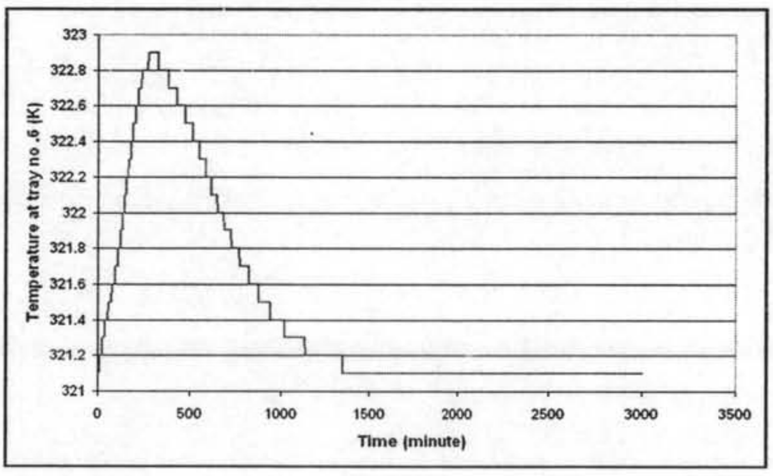

Figure 4.54 Response curve of temperature (controllcd variable) of tray no.6 of dynamic matrix control with disturbance of changing feed flowrate from 0.09 to 0.1 (kg-mol/minute).

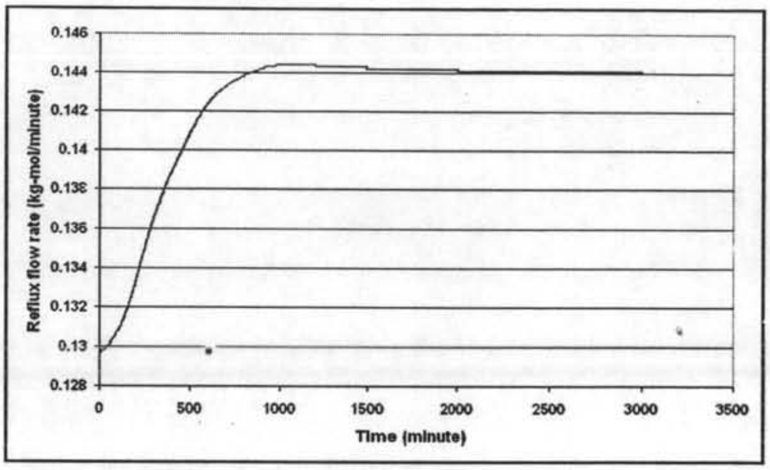

Figure 4.55 Response curve of reflux flowrate (manipulated variable) of dynamic matrix control of temperature of tray no.6 with disturbance of changing feed flowrate from 0.09 to 0.1 (kg-mol/minute).

The results of the DMC of temperature of tray no.25 with the disturbance of changing feed flowrate from 0.09 to 0.1 (kg-mol/minute) are shown in Figures 4.56 and 4.57. The response curves of the controlled variable have no oscillation.

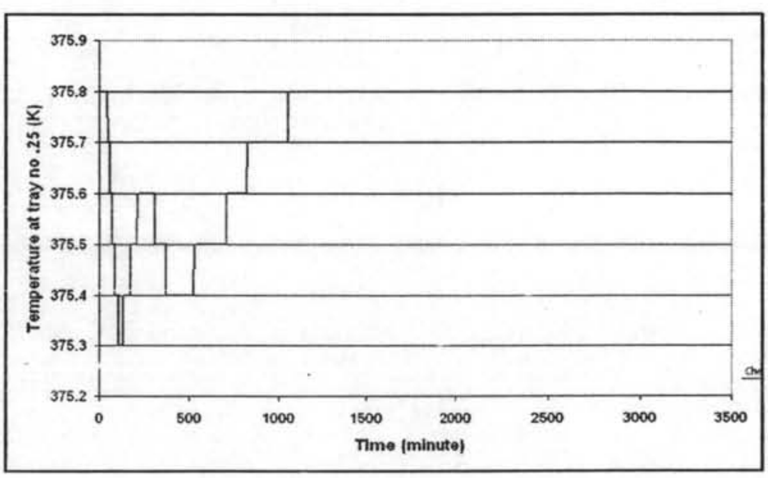

Figure 4.56 Response curve of temperature (controlled variable) of tray no.25 of dynamic matrix control with disturbance of changing feed flowrate from 0.09 to 0.1 (kg-mol/minute).

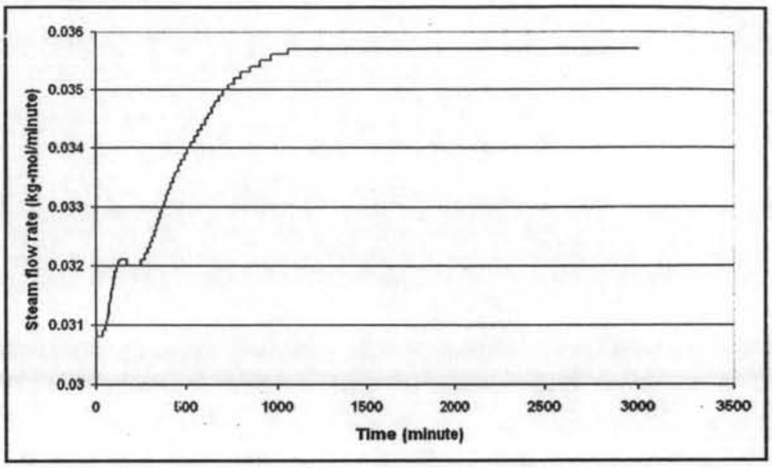

Figure 4.57 Response curve of steam flowrate (manipulated variable) of dynamic matrix control of temperature of tray no.25 with disturbance of changing feed flowrate from 0.09 to 0.1 (kg-mol/minute).

Table 4.7 IAE value of temperature of tray no.6 and no.25 with disturbance of changing feed flowrate from 0.09 to 0.01 (kg-mol/minute)

Tray	IAE (K*min)	
No.	Cascade	DMC
6	1177	1037
25	774	257

From Table 4.7, the IAE values show that the DMC is a faster control system than the cascade control system in reducing the error of the controlled variable.

4.1.5.3 Disturbance of Changing Setpoint Tray No.6

The results of the DMC of tray no.6 with the disturbance of changing setpoint of tray no.6 from 321.3 to 323.3 (K) are shown in Figures 4.58 and 4.59. The response curves of the controlled variable give few oscillation and low overshoot.

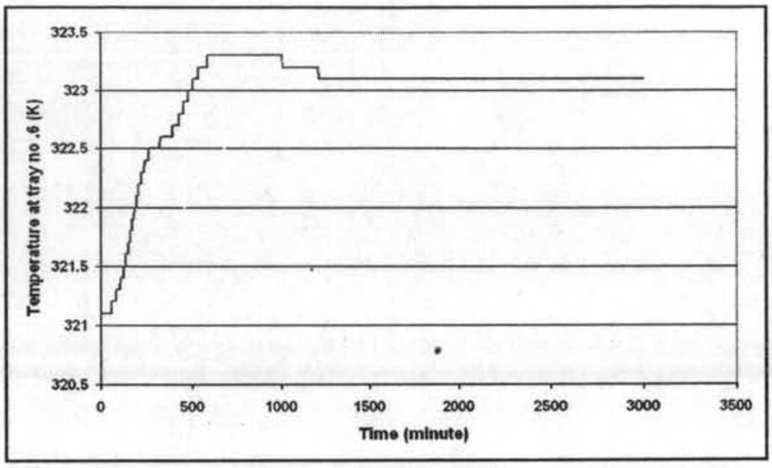

Figure 4.58 Response curve of temperature (controlled variable) of tray no.6 of dynamic matrix control with disturbance of changing setpoint of tray no.6 from 321.1 to 323.1 (K).

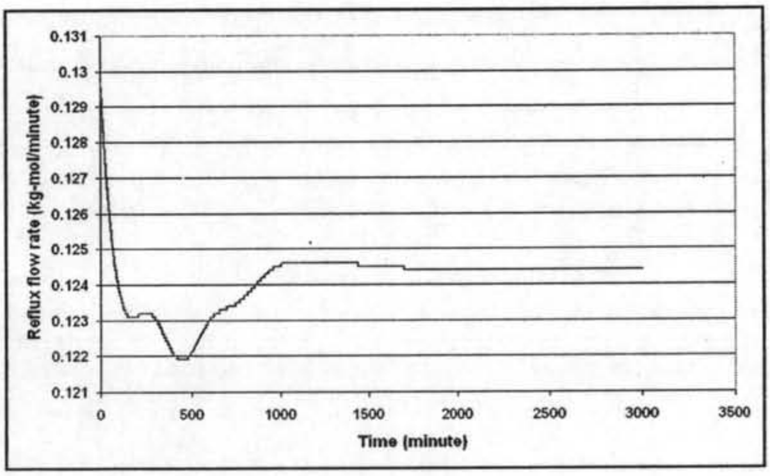

Figure 4.59 Response curve of reflux flowrate (manipulated variable) of dynamic matrix control of temperature of tray no.6 with disturbance of changing setpoint of tray no.6 from 321.1 to 323.1 (K).

The results of the DMC of tray no.25 with the disturbance of changing the setpoint of tray no.6 from 321.3 to 323.3 (K) are shown in Figures 4.60 and 4.61. The response curves of the controlled variable give few oscillation and low overshoot.

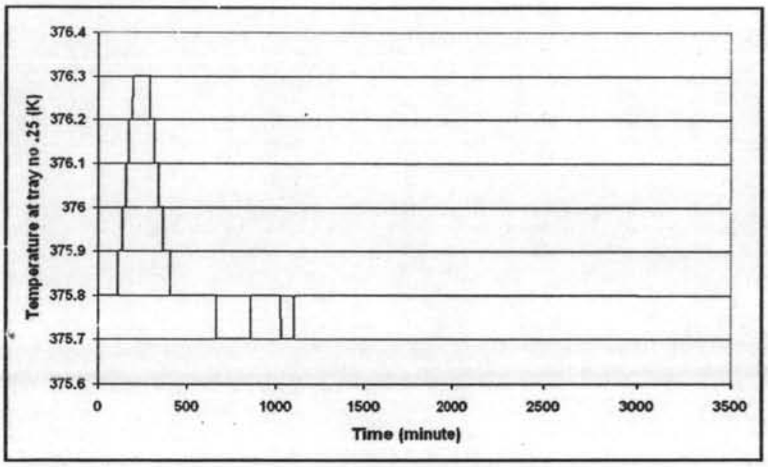

Figure 4.60 Response curve of temperature (controlled variable) of tray no.25 of dynamic matrix control with disturbance of changing setpoint of tray no.6 from 321.1 to 323.1 (K).

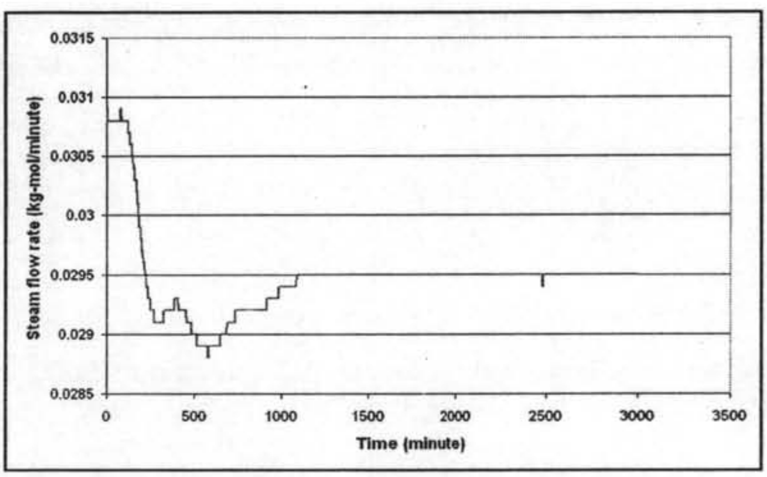

Figure 4.61 Response curve of steam flowrate (manipulated variable) of dynamic matrix control of temperature of tray no.25 with disturbance of changing setpoint of tray no.6 from 321.1 to 323.1 (K).

Table 4.8 IAE value of temperature of tray no.6 and no.25 with disturbance of changing setpoint of tray no.6 from 321.1 to 323.1(K)

Tray	IAE (K*min)	
No.	Cascade	DMC
6	703	599
25	277	123

From Table 4.8, the IAE values of the controlled variables from the DMC are lower than the cascade control. These mean that the DMC reduces the error of controlled variable faster than the cascade control.

4.1.5.4 Disturbance of Changing Steam Flowrate

The results of the DMC of tray no.6 with the disturbance of changing steam flowrate from 0.0309 to 0.02 (kg-mol/minute) are shown in Figures 4.62 and 4.63. The response curve is the same as the response curve of the cascade control in the case of steam flowrate change.

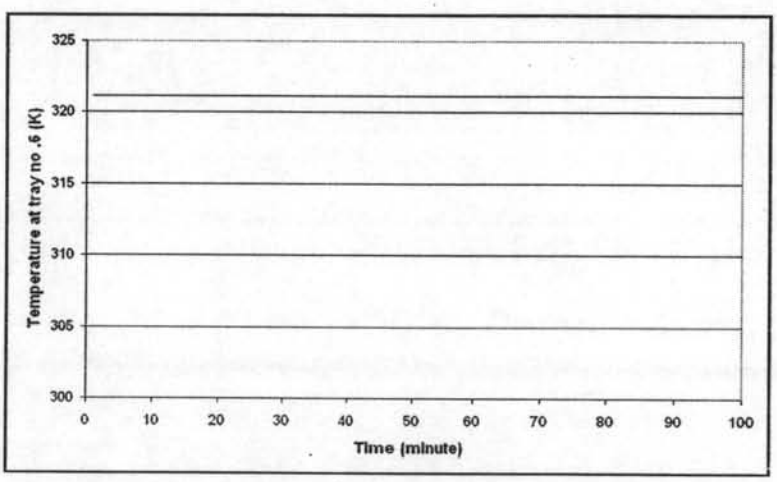

Figure 4.62 Response curve of temperature (controlled variable) of tray no.6 of dynamic matrix control with disturbance of changing steam flowrate from 0.0309 to 0.02 (kg-mol/minute).

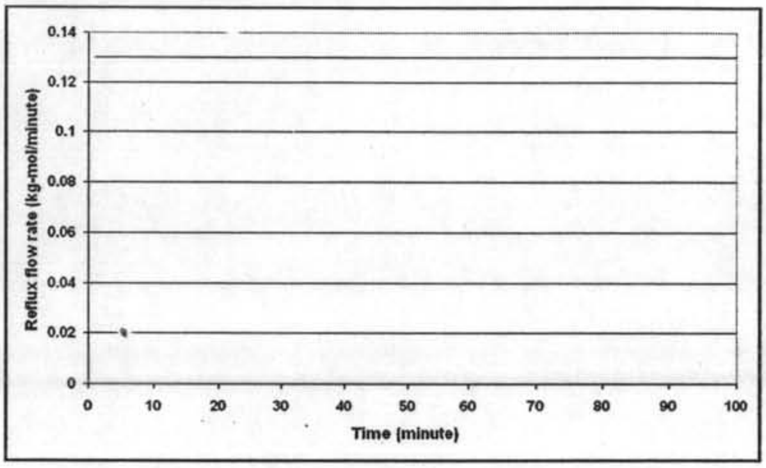

Figure 4.63 Response curve of reflux flowrate (manipulated variable) of dynamic matrix control of temperature of tray no.6 with disturbance of changing steam flowrate from 0.0309 to 0.02 (kg-mol/minute).

The results of the DMC of tray no.25 with the disturbance of changing steam flowrate from 0.0309 to 0.02 (kg-mol/minute) are shown in Figures 4.64 and 4.65. The response curve is the same as the response curve of the cascade control in the case of steam flowrate change.

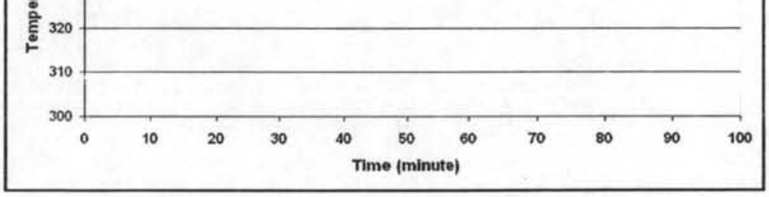

Figure 4.64 Response curve of temperature (controlled variable) of tray no.25 of dynamic matrix control with disturbance of changing steam flowrate from 0.0309 to 0.02 (kg-mol/minute).

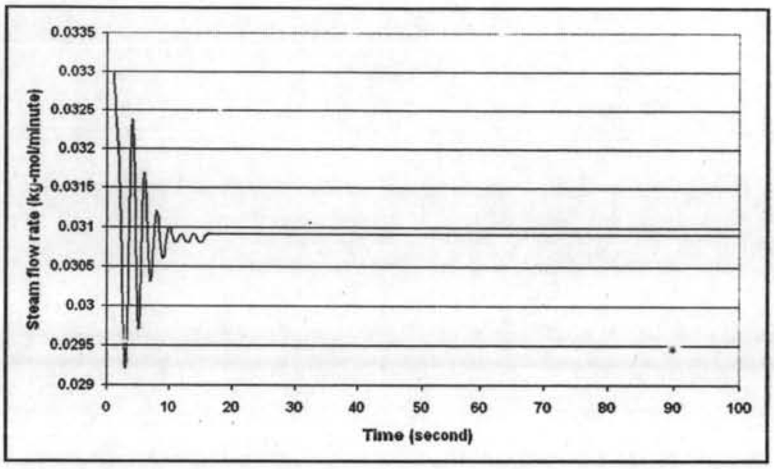

Figure 4.65 Response curve of steam flowrate (manipulated variable) of dynamic matrix control of temperature of tray no.25 with disturbance of changing steam flowrate from 0.0309 to 0.02 (kg-mol/minute).

From Figures 4.62 to 4.65, the secondary controller eliminated the effect of the disturbance of steam flowrate change before it affected the temperature at tray no.6 and no.25. The IAE values of all controllers in this case are 0 K*minute.